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A STUDY OF PASSENGER AIRCRAFT CARGO HOLD ENVIRONMENTS

(BY: E^X^PONENT FAILURE ANALYSIS ASSOCIATES)

Failure Analysis Associates

A Study of Passenger Aircraft Cargo Hold Environments

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Prepared for

David B. Weinberg, Esq.
Howrey Simon Arnold & White
1299 Pennsylvania Avenue, NW
Washington, D.C. 20004

Prepared by

Celina Mikolajczak
Dennis Moore, Ph.D., P.E.
Exponent® Failure Analysis Associates
149 Commonwealth Drive
Menlo Park, CA 94025

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Acronyms and Abbreviations

CFR	Code of Federal Regulations
DOT	Department of Transportation
Exponent	Exponent® Failure Analysis Associates
FAA	US Federal Aviation Administration
FAR	Federal Aviation Regulations (14 CFR)
LAX	Los Angeles International Airport
LFL	Lower Flammability Limit
NTSB	National Transportation Safety Board
PRBA	Portable Rechargeable Battery Association
RSPA	Research and Special Programs Administration
UFL	Upper Flammability Limit

1 Executive Summary

At the request of the Portable Rechargeable Battery Association (PRBA), Exponent® Failure Analysis Associates (Exponent) has reviewed the available literature concerning aircraft cargo hold environments as a first step toward understanding the implications of lithium-ion battery cell venting in a cargo hold fire situation. Exponent has researched cargo hold construction, suppression system behavior, and cargo loading practices for aircraft likely to be carrying bulk shipments of lithium-ion cells. In particular, Exponent has examined the conditions in lower lobe, Class C, cargo compartments found on passenger aircraft, as these compartments are inaccessible in flight, and cannot be depressurized in order to suppress a fire. Exponent is in the process of obtaining information from PRBA members concerning their bulk shipping practices. Furthermore, Exponent has reviewed information concerning lithium-ion cell vent gas composition and the generally available information concerning the flammability of those gases. Finally, Exponent has reviewed published literature concerning cargo hold fire suppression testing.

Based on the reviewed information, Exponent has concluded the following:

1. A cargo hold fire could produce temperatures near the ceiling of the hold that might cause lithium-ion cells to vent, if they were subjected to these temperatures for a sufficient length of time. However, the heating of lithium-ion cells would be retarded by the presence of surrounding packaging and the heat capacities of the cells themselves. The initial rate of cell heating would be highly dependent upon packaging details.

2. Pallets of lithium-ion cells or batteries are shipped in large Class C cargo holds (on passenger aircraft) where palletization and containerization, rather than bulk loading, of cargo and baggage is typical. Baggage and cargo are not typically mixed on pallets or in containers; rather, they are segregated to allow for efficient ground handling. Therefore, it is unlikely that a pallet of lithium-ion cells or battery packs would be subjected to direct flame impingement from an article of burning passenger luggage during the early initiation stage of a fire. Thus, lithium-ion cells or battery packs would be unlikely to vent prior to a cargo hold fire being detected and Halon 1301 being discharged.

3. Shortly after a fire is detected in a Class C cargo hold, the hold is flooded with Halon 1301 suppressant, which significantly reduces the possibility that a flame will be able to propagate through the cargo hold atmosphere. After Halon is released, the compartment atmosphere is resistant to flame propagation despite the addition of flammable gases such as the products of incomplete combustion resulting from smoldering, the propellants from ruptured aerosol cans, or the vent gases from lithium-ion cells.

4. Shortly after a fire begins in a cargo hold, the oxygen concentration in the hold begins to drop, and carbon dioxide and water concentrations resulting from the combustion process begin to increase. These effects significantly reduce the possibility that a flame will be able to propagate through the cargo hold atmosphere. After the oxygen concentration drops by a sufficient amount, the compartment atmosphere is resistant to flame propagation despite the addition of flammable gases such as the products of incomplete combustion resulting from smoldering, the propellants from ruptured aerosol cans, or the vent gases from lithium-ion cells as long as the compartment walls are not breached and air is not added.

5. Smoldering Class A combustibles such as paper, cardboard, plastics, and textiles will fill a closed compartment with flammable products of incomplete combustion. Without addition of oxygen, the resulting mixture will be above the UFL, such that the addition of fuel compounds (from cell venting or release of aerosol propellants) will not increase the possibility that a flame will be able to propagate through the cargo hold atmosphere. Rather, the addition of fuel will make the mixture more fuel rich and move it further from the flammable range.

6. Lithium-ion battery cells are specifically designed to vent, rather than rupture, upon overheating. The FAA aerosol can simulator is designed to mimic the effect of an aerosol can rupture, and as such is considered an aggressive test for suppression of a luggage fire that interacts with an aerosol can. The FAA is particularly concerned with aerosol can rupture early in the initiation of a fire, prior to the fire's detection or the deployment of Halon1301. Aerosol can simulator testing shows that once Halon has been released into a compartment, the propellant gas will not ignite.

2 Introduction

In December 1999, the US Department of Transportation (DOT) Research and Special Programs Administration (RSPA) published a final report entitled, “Threat Assessment of Hazardous Materials Transportation in Aircraft Cargo Compartments” (Threat Assessment Report)[1]. This report contains a list of recommendations for improving cargo transport safety, including improving shipper compliance with current regulations, reassessment of existing hazardous materials regulations, and adding or improving fire suppression systems in all cargo holds.

Included in the RSPA Threat Assessment Report was a summary of all known fire incidents (internationally) in which hazardous materials were located inside an aircraft cargo hold, or were being loaded or unloaded from an aircraft cargo hold. The RSPA report lists 31 incidents of various magnitudes, including those where smoke was observed emitting from a package or suitcase during handling. The Threat Assessment Report indicates that 6 of these 31 incidents involved an in-flight fire in a cargo hold.

The RSPA report also lists the known cargo fire incidents not caused by hazardous materials from 1970 to 1999. There were 17 such reported fires, ranging in severity from a localized burn spot on a cargo-heating blanket to an incident resulting in 301 fatalities. RSPA estimates that in Class C aircraft cargo compartments (compartments with suppression systems), there have been 3 instances of independent fires in 57 million departures, and that the probability of such a fire is 1 in 19 million departures. Similarly, for Class D aircraft compartments (compartments without suppression systems), there have been 9 incidents in 242 million departures, and that the probability of such a fire is 1 in 27 million departures. If Class C and D cargo hold incidents are combined, the estimated probability of an independent fire (one not caused by a hazardous material) is 1 in 25 million departures.

RSPA has developed probability factors for “worst likely” scenarios. For example, RSPA estimates that the probability of a fire not being suppressed in a Class C cargo hold by the suppression system is 4%. When combined with the probability of an independent fire in the cargo hold, the probability of having an unsuppressed fire in a Class C cargo hold is 1 in 480 million departures. Assuming average flight durations of 2-4 hours, the estimated probability of an unsuppressed fire in a Class C cargo hold is in the range of 1 in 0.96 to 1.92 billion flight hours. The RSPA report goes on to assign a number of probability factors based upon the hazardous material considered and the cargo hold class. This includes those for an unsuppressed fire breaching the cargo hold, an unsuppressed fire causing the transfer of toxic materials (including smoke) to the cockpit and cabin, toxic materials in the cockpit or cabin resulting in a life threatening situation, an explosion, and an explosion that is sufficiently severe to destroy the aircraft. As a point of reference, the US Federal Aviation Administration (FAA)

[1] “*Threat Assessment of Hazardous Materials Transportation in Aircraft Cargo Compartments*,” DOT-VNTSC-RSPA-99-01, December 1999.

has typically deemed a risk of 1 in 1 billion flight hours acceptable for any single failure to cause the loss of an aircraft.

Although the base probability of a fire causing loss of an aircraft is of the same order as the acceptable risk for other potentially catastrophic incidents, the regulatory agencies have exhibited a heightened interest in cargo hold fires in recent years. The April 1999 fire involving lithium batteries at Los Angeles International Airport (LAX) prompted the National Transportation Safety Board (NTSB) to recommend that DOT reassess the hazardous material classification and shipping exemptions on both lithium primary and lithium-ion secondary batteries. The DOT has raised concerns over the potential for lithium metal and lithium-ion cells to initiate a cargo hold fire or, if exposed to an independent fire, to significantly increase its severity.

This report addresses, in part, the DOT concern over lithium-ion cells exposed to an independent, lower lobe, Class C cargo hold fire, in a passenger aircraft. Since lithium-ion cells do not contain metallic lithium, exposure to an independent fire will not result in a lithium metal fire. However, lithium-ion cells do contain a hydrocarbon-based electrolyte that may vent if the cell is exposed to a sufficiently high temperature. The likelihood of cell venting during an independent cargo hold fire, the possibility that the resulting gas mixture will be flammable, and the further possibility that the fire severity will be affected by the presence of bulk quantities of lithium-ion cells depend upon a number of factors: cargo hold construction, cargo hold loading practices, pallet and container configuration, vent gas composition and flammability, and cargo hold fire suppression systems. This report discusses these factors and the results of cargo hold fire tests conducted by the FAA. Considering the typical packaging of lithium-ion cells and the fact that they are shipped in a 20%- 50% state of charge, this report concentrates on the venting of cells and their potential contribution to a fire started elsewhere in a cargo hold of a passenger aircraft.

3 Cargo Hold Construction

The requirements for aircraft cargo holds are found in US Code of Federal Regulations (CFR), Title 14, Part 25 (FAR 25), "Airworthiness Standards: Transport Category Airplanes." The classifications of cargo holds are specifically described in FAR 25.857. Aircraft cargo holds are classified based on whether the compartment can be easily observed by crewmembers, whether automatic fire detection systems are present, whether automatic fire suppression systems are present, and whether a compartment liner is required. Class C compartments are typical cargo compartments found on passenger aircraft. They are equipped with fire detection systems that notify the flight crew within 1 minute of the start of small smoldering fires, such as single suitcase fires. The compartments are equipped with fixed fire suppression systems that can be remotely activated by the crew. Class C compartments also have flame-resistant liners and the means to shut off airflow to the compartment. Although smaller aircraft cargo holds were traditionally allowed to be without suppression systems (Class D), in 1998 the FAA published a Final Rule amending Parts 25, 121, and 125 of the FAR's and issued an Airworthiness Directive requiring the conversion of all Class D cargo holds on passenger aircraft to Class C Cargo holds by March 19, 2001. Class E cargo holds, found on the main decks of cargo aircraft, continue to be allowed to operate without suppression systems. Operators are allowed to depressurize these compartments in order to suppress fires.

3.1 Cargo Hold Sizes

Aircraft cargo holds vary in size and configuration depending upon aircraft line and model. Typically, an aircraft will have two or three cargo holds in the lower lobe (the volume beneath the main cabin floor). The forward hold is forward of the wing, while the center or aft hold is located behind the wing. In a number of larger aircraft there is an additional rear bulk cargo hold located aft of the center hold. This may be separated from the main hold by a net, effectively making the hold one volume from a fire perspective. Alternatively, there may be some sort of bulkhead or barrier separating the two compartments. Figure 1 shows some typical locations of lower lobe cargo holds. Figure 2 shows a typical cargo hold location in an aircraft fuselage viewed in cross section.

Unoccupied cargo hold volume will affect the rate of oxygen consumption during a fire as well as Halon concentration. Oxygen concentration in a small volume will drop faster than oxygen concentration in a large volume. Initial Halon concentration will be dependant upon the volume of an empty hold, which determines the total amount of Halon released into the hold, as well as the amount of volume displaced by the cargo. Table 1 lists lower lobe cargo hold sizes for a variety of commercial airliners.[2]

[2] Data is compiled from *Jane's All the World's Aircraft 2000-2001, Jane's All the World's Aircraft 1989-1990*, and the US Department of the Air Force, "Load Planning Guide" for the Civil Reserve Air Fleet, 1992.

In some aircraft, such as the 747, the front and center holds have open floors with exposed aircraft frames. All cargo or baggage placed into these compartments must be containerized, palletized, or placed on a pallet subfloor. In other aircraft, such as the DC-10 and the 707, all of the compartments have solid floors. Baggage can be bulk loaded directly onto the floor of these types of compartments or placed in commercial baggage containers or on pallets. Forward, center, and aft cargo holds range in size from approximately 250 to 3,000 ft^3. Typically, individual cargo hold volumes in narrow body aircraft and commuter aircraft are 800 ft^3 or less.

The rear bulk compartments present on many larger aircraft are typically used by air carriers for the transport of items such as spare parts kits, wheels, and crew baggage, rather than for the transport of passenger baggage or cargo. Typically, these compartments range in size from approximately 400 to 1000 ft^3. In the 747, the rear bulk compartment is separated from the center compartment by a removable curtain and has a solid subfloor that slants up toward the tail of the fuselage. In some DC-10's, the rear bulk compartment is separated from the center cargo hold by a curtain, while on other DC-10's the two compartments are separated by a solid wall.

Table 1: Aircraft cargo hold sizes[2]

Aircraft	Cargo Hold	Volume (ft^3)	Max Height (in)
Airbus A300-600	Forward	2,652	69
	Center	1,942	69
	Rear (Bulk)	611	69
Airbus A310	Forward	1,776	67.25
	Center	1,218	65.75
	Rear (Bulk)	611	Not avail.
Airbus A320	Forward	469	Not avail.
	Aft	900	Not avail.
Airbus A318	Forward	247	Not avail.
	Aft	526	Not avail.
Airbus A321	Forward	813	Not avail.
	Aft	1025	Not avail.
Boeing 707-300	Forward	835	Not avail.
	Aft	865	Not avail.
Boeing 727-200	Forward	710	Not avail.
	Aft	815	Not avail.
Boeing 737-200	Forward	370	Not avail.
	Aft	505	Not avail.

Aircraft	Cargo Hold	Volume (ft^3)	Max Height (in)
Boeing 737-300	Forward	425	Not avail.
	Aft	643	Not avail.
Boeing 737-600	Combined	720	Not avail.
Boeing 737-700	Combined	966	Not avail.
Boeing 737-800	Combined	1,555	Not avail.
Boeing 737-900	Combined	1,835	Not avail.
Boeing 747-100/200B/300/400	Forward	2,768 (upper galley) 2,178 (lower galley)	Not avail.
	Center	2,422 (upper galley) 1,742 (lower galley)	Not avail.
	Rear (Bulk)	1,000 (upper galley) 800 (lower galley)	Not avail.
Boeing 747 SP	Forward	1,730	68
	Center	1,730	68
	Rear (Bulk)	400	Not avail.
Boeing 757-200	Forward	699	Not avail.
	Aft	971	Not avail.
Boeing 757-300	Forward	1,071	Not avail.
	Aft	1,299	Not avail.
Boeing 767-200	Forward	1,931	Not avail.
	Center	1,588	Not avail.
	Rear (Bulk)	430	Not avail.
Boeing 767-300	Forward	2,537	Not avail.
	Center	2,251	Not avail.
	Rear (Bulk)	430	Not avail.
Lockheed L-1011-100	Forward	1,600 (lower galley) 3,030 (upper galley)	66
	Center	1,600	66
	Rear (Bulk)	700 (lower galley) 635 (upper galley)	Not avail.
Lockheed L-1011-500	Forward	2,400	66
	Center	1,400	66
	Rear (Bulk)	435	Not avail.
DC-9-30	Combined	895	Not avail.

Aircraft	Cargo Hold	Volume (ft^3)	Max Height (in)
DC-9-40	Combined	1019	Not avail.
DC-9-50	Combined	1174	Not avail.
MD-81/82	Forward	464	Not avail.
	Center	346	Not avail.
	Rear	443	Not avail.
McDonnell Douglas DC-10	Forward	1,373 (lower galley) 3,059 (upper galley)	64
	Center	1,592 (lower galley) 1,944 (upper galley)	64
	Rear (Bulk)	805 (lower galley) 510 (upper galley)	Not avail.

3.2 Cargo Hold Liners

All Class C (and Class D) compartments are required to have a cargo liner, which is an enclosure designed to isolate the compartment from the structure and other sections of the aircraft. The space between the aircraft fuselage and the cargo hold liner (cheek area) may contain a variety of components including wiring, control cables, hydraulic lines, and fuel lines. FAR 121.314 requires that all Class C compartments larger than 200 ft^3 must have ceiling and sidewall liners constructed of glass fiber reinforced resin, materials which meet the flammability requirements specified in FAR Part 25, Appendix F, or, if approved prior to 1989, aluminum. Appendix F requires that Class C ceiling liners, sidewall liners, and floor panels pass a vertical flame test,[3] and that the floor panels (which must also be separated from the aircraft structure) must pass a 45-degree flame test.[4] These requirements have led to the removal of Kevlar and Nomex liners from cargo holds,[5] as FAA testing has shown that these liners are more susceptible to burn-through than fiberglass liners.[6, 7]

[3] In the vertical flame test, the lower edge of a sample is subjected to a 1550 F flame for 60 seconds. The burn length must be less than 8 inches; any material that is burning must stop within 15 seconds after the flame is removed, and any drippings cannot flame for more than 5 seconds after falling.

[4] In the 45-degree test, a 1550 F flame is applied for 30 seconds. The flame must not penetrate the material, the material may not glow for more than 10 seconds (on the non-flame side), and the flame side may not burn for more than 15 seconds after removal of the flame.

[5] Hill, R.G. and D.R. Blake, "A Review of Recent Civil Air Transport Accidents/Incidents and Their Fire Safety Implications," *Proceedings of the Fourth International Symposium on Fire Safety Science*, 1994, pp. 85-94.

[6] Blake, David R., *Suppression and Control of Class C Cargo and Compartment Fires*, DOT/FAA/CT-84/21, U.S. Dept. of Transportation, FAA, February 1985.

[7] Blake, David R. and Richard Hill, *Fire Containment Characteristics of Aircraft Class D Cargo Compartments*, DOT/FAA/82-156, FAA Technical Center, March 1983.

3.3 Cargo Hold Airflow

Figure 3 depicts the general aircraft flow path for a passenger aircraft. Bleed air from the engines is expanded and cooled in air-cycle machines. The air flows into the aircraft cabin through long distribution plena and individual seat air controls. It leaves the cabin through floor vents, located where the main cabin floor meets the fuselage, flows into the lower lobe cheek area, and then exits the aircraft entirely through the outflow valve located in the lower fuselage. The opening of the outflow valve is controlled to maintain the pressure in the aircraft at the desired level. In the DC-10/MD-11, the outflow valve is located forward of the wing on the left hand side of the aircraft. On most other aircraft, the outflow valve(s) is located in the rear of the aircraft. The location of the outflow valve and the cargo hold will significantly affect the rates of flow between the fuselage and the cargo liner. Near the outflow valve, the flow will be equal to the total flow into the aircraft, whereas a cargo hold away from the outflow valve will have less flow around it. This will affect both the leakage rate and the cooling of the liner.

Atmospheric pressure at sea level is 14.7 psi. At a cruising altitude of approximately 36,000 ft, atmospheric pressure is approximately 3.3 psi. A typical passenger aircraft is pressurized to approximately 7.5 to 8.5 psi over the outside pressure, thus the cabin (and also cargo hold) pressure will be approximately 10.8 to 11.8 psi. A passenger aircraft cannot be depressurized to fight a fire. Thus, most aircraft cargo will be in an environment of between 11 and 15 psi.

The ventilation rates into the cabin are determined by the amount of air required to keep concentrations of carbon monoxide below 1 part in 20,000 parts air[8]. In practice, this requires approximately 10 CFM of fresh outside air per passenger, with an additional 10 CFM of re-circulated, filtered air.[9]

Additionally, some aircraft are equipped with a “pet air system” that forces additional air into the cargo compartment. This system is used to create a ventilation environment suitable for the transport of live animals in the cargo hold. In case of cargo hold smoke detector activation, the crew has the capability to shut down the pet air system.

Since cargo hold liners are made of panels that are fastened to the fuselage ribbing, the compartments are not airtight and, even without a “pet air” system, they have a finite leak rate. The FAA has measured a leakage rate of 80 CFM (4800 CFH) from an in service Class C compartment of approximately 2357 ft^3.[6] Pacific Scientific Company has measured leakage rates in a number of (originally) Class D compartments during a conversion process to Class C. These measurements were made during flight tests of forward and aft cargo compartments of DC9-30, 737-300, MD82, and 727-200 aircraft. Pacific Scientific Company measured rates ranging from 4.7 CFM (280 CFH) to 100 CFM (6000 CFH).[10] They found leaks in a number of areas: door seals, drain holes in doorframes, and mounting areas of the smoke detectors.

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[8] CFR Title 14 Part 23, Section 831 (FAR 23.831).

[9] American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), HVAC Applications, 1995.

[10] Meserve, W.J., “Lessons Learned from In-Service D to C Conversions,” Pacific Scientific Company, n.d.

In addition to leak rates, the inflow or outflow of gases depends on the pressurization of the aircraft. As the aircraft ascends and cabin pressure is reduced, some of the gases inside the cargo hold will exit. Similarly, even in the absence of leaks, as the aircraft descends, fresh air will be admitted to the cargo hold as the pressure increases and the volume of gases in the cargo hold is compressed.

4 Typical Cargo Hold Loading Practices

Baggage and cargo is loaded into an aircraft in one of three ways: as individual pieces (bulk loading), as individual pieces loaded into standard sized containers (containerized), or as assembled and packaged cubes loaded onto pallets (palletized). Bulk loading of luggage is almost universal on smaller aircraft. The use of containers and pallets is particularly compatible with mechanical baggage and cargo loading equipment, and is used for most cargo and baggage on wide-body aircraft to reduce manpower and loading and unloading times. Portions of the cost savings to the airlines resulting from palletization and containerization of freight are typically passed on to the shippers as discounted shipping rates.[11] Small pieces of freight are often consolidated by shippers or by airline airfreight services into larger single units (pallets or containers) for transport. Since passenger baggage and cargo are processed separately, containerization and palletization results in baggage and cargo segregation.

4.1 Containerized Cargo

Aircraft cargo containers are available in a series of standard sizes. Figure 4 depicts the dimensions of some typical lower lobe containers. All of these containers have an overall height of 64 inches. This results in only a few inches of clearance between the top of a container and the ceiling of a cargo hold. LD-3 containers are the most commonly used on passenger aircraft and can be used in 747, 767, 777, DC-10, MD-11, L-1011, and Airbus A-300, A-310, and A-340 aircraft.[12] They have an internal volume of between 145 and 158 ft^3 (nominal volume of 150 ft^3), and are limited to carrying 3,500 lbs. Containers can be loaded with freight at a shipper's location and sent to the airport ready for loading. For reasons of security, containers loaded by a shipper are typically sealed.[11]

4.2 Palletized Cargo

A typical commercial aircraft pallet is 1 inch thick, 88 or 96 inches wide, and 125 inches long.[11] It has a useable area of 84 (or 92) by 121 inches. The remaining area is consumed by tie down hardware. The height of material stacked on a single pallet is limited by the cargo hold door height. The weight of material stacked on a single pallet is limited by loading requirements for specific aircraft, and the placement of the pallet in the aircraft.

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[11] *Air Cargo from A to Z*, 6th printing, Air Transport Association of America.

[12] Blake, David R., *Evaluation of Fire Containment of LD-3 Cargo Containers*, DOT/FAA/CT-TN83/38, FAA Technical Center, October 1983; and the US Department of the Air Force, "Load Planning Guide" for the Civil Reserve Air Fleet, 1992.

4.3 Typical Li-Ion Cell/Battery Shipping Practice

Information received to date concerning shipping practices of PRBA members suggests that large shipments (often trans-Pacific) of lithium-ion cells or battery packs are accomplished on pallets, and occasionally in containers. Pallets typically contain multiple layers of boxes and may be enclosed in a cardboard overpack, wrapped in plastic, or netted to secure the boxes to the pallet. Smaller shipments of individual boxes (US domestic) are sent through shipping companies such as UPS and Federal Express. These shippers own and use dedicated cargo aircraft exclusively, and thus can fight fires using depressurization. Conditions in main cabin cargo compartments (Class E) are not the subject of this report.

5 Lithium-Ion Cell/Battery Flammability

5.1 Vented Electrolyte Composition

In a recent report[13] from Sandia National Labs, Crafts, Borek and Mowry describe the composition of vent gas from a noncommercial cell subject to heating at a rate of 1 C/min up to a temperature of 200 C. The tested cells had the following composition:

Table 2: Composition of Li-ion cell used for Sandia testing

Cathode:	84 wt% $LiNi_{0.85}Co_{0.15}O_2$
	Balance of graphite and carbon black
Anode:	Blend of SFG-6 and MCMB-6 carbons
Electrolyte:	1.0M $LiPF_6$ in 1:1 EC/DEC
Separator:	Supplied by Celgard
Binder:	PVDF

The Sandia researchers found that the vent gas included hydrogen, carbon monoxide, carbon dioxide, methane, ethylene, ethane, propylene, and C4 and C5 hydrocarbons (Figure 5). A large proportion of the vent gas was carbon dioxide. Crafts, et al, did not report the relative quantities of each compound produced during cell venting.

In experiments concerning gas generation during the first charge of Li-ion cells, Jehoulet, et al,[14] of SAFT detected the formation of ethylene and propylene gas, as well as small quantities of hydrogen, oxygen, nitrogen, carbon monoxide, methane and carbon dioxide. The SAFT researchers proposed a mechanism for the formation of ethylene and propylene gas from electrolyte to account for the observed quantities of these gases. Of the identified vent gases, the flammable species include ethylene, propylene, methane, ethane, the C4 and C5 hydrocarbons, hydrogen, and carbon monoxide. Carbon dioxide is not flammable, and is used worldwide as a fire suppressant.

[13] Crafts, C., T. Borek, and C. Mowry, "Safety Testing of 18650-Style Li-Ion Cells," Sandia National Laboratories, SAND2000-1454C, May 2000.

[14] Jehoulet, C., P. Biensan, J.M. Bodet, M. Broussely, C. Moteau, and C. Tessier-Lescourret, "Influence of the solvent composition on the passivation mechanism of the carbon electrode in lithium-ion prismatic cells," *Proceedings of the Symposium on Batteries for Portable Applications and Electric Vehicles*, 1997.

5.2 Flammability Limits

When a cell vents, the released gases will mix with the surrounding atmosphere, and depending upon a number of factors including fuel concentration, oxygen concentration, gas temperature, and gas pressure, the resulting mixture may or may not be flammable. The flammability limits of a gaseous fuel/air mixture are the prime measures for ascertaining whether that mixture is combustible. Fuel/air mixtures have two flammability limits: a lower flammability limit (LFL) or lean limit, below which the concentration of fuel is too low to allow flame propagation, and an upper flammability limit (UFL) or rich limit, where the concentration of fuel is too high for the available oxygen to allow flame propagation. If the fuel concentration in a particular gas mixture is between the LFL and UFL, that mixture is ignitable. If a competent ignition source is present, a flame can begin and propagate through the mixture. If the fuel concentration in a particular gas mixture is outside the range bounded by the LFL and UFL, then that mixture will not be ignitable. At each limit, the scarcity of one reactant results in a rate of heat generation that is just low enough to be exactly balanced by the rate of heat transfer away from the reaction zone.

Every fuel has unique flammability limits in a specific oxidizing atmosphere, under specific conditions of temperature and pressure. These limits are determined by the fuel's specific combustion chemistry and the heat transfer properties of the surrounding atmosphere. Since the details of combustion chemistry can be very complex, flammability limits are determined empirically with standardized tests.[15] Table 3 lists flammability limits for various fuel/air mixtures at atmospheric pressure and room temperature, which will be similar to the conditions encountered in most passenger aircraft cargo holds.

Table 3: Flammability limits of fuel/air mixtures[16]

Compound	Lower Flammability Limit (Fuel Volume Percent)	Upper Flammability Limit (Fuel Volume Percent)
Hydrogen	4.0	75.0
Carbon Monoxide	12.5	74.0
Methane	5.3	15.0
Ethylene	3.1	32.0
Ethane	3.0	12.5
Propylene	2.4	10.3
C4 hydrocarbons	~ 1.6 – 1.9	~ 8.4 – 9.7
C5 hydrocarbons	~ 1.4 – 1.5	~ 7.5 – 8.7

[15] ASTM E681 describes a standard test method for determining flammability limits.
[16] For atmospheric pressure, room temperature, and upward propagation in a tube. Lewis, B. and G. von Elbe, *Combustion, Flames and Explosions of Gases*, 2nd Edition, Academic Press, New York, 1961.

Oxygen concentration, inert diluent composition, temperature, pressure, and the presence of specific suppressant chemicals affect flammability limits. If oxygen concentration of the mixture drops due to its replacement by a specific inert diluent, such as nitrogen, carbon dioxide, or non-combustible products of combustion, the flammability limits of the mixture narrow until the oxygen concentration drops to a level below which a flame will not propagate, regardless of the fuel concentration. Figure 6 through Figure 9 show how the flammability limits of carbon monoxide, methane, ethylene, and propylene narrow as oxygen concentration is reduced by the addition of excess inert gases. In these figures, the area between the lower and upper limits (inside the flammability limit curve) is the region of flammable mixtures (note that the terms "flammable" and "inflammable" are equivalent). A mixture that falls outside of this region will not support a propagating flame.

The maximum oxygen concentration at which the mixture will not be flammable at any fuel concentration is referred to as the "maximum safe percentage of oxygen." Table 4 lists maximum safe percentages of oxygen in mixtures of combustibles with air and carbon dioxide or nitrogen at atmospheric pressure and room temperature. (With no added diluent, air contains ~21% oxygen.)

Table 4: Maximum safe percentage of oxygen in mixtures of combustibles with air and carbon dioxide or nitrogen[17]

Compound	Volume % of Oxygen with Carbon Dioxide Diluent	Volume % of Oxygen with Nitrogen Diluent
Hydrogen	5.9	5.0
Carbon Monoxide	5.9	5.6
Methane	14.6	12.1
Ethylene	11.7	10.0
Ethane	13.4	11.0
Propylene	14.1	11.5
C4 and C5 hydrocarbons	14.5	12.1

In general, increasing the initial gas temperature of a fuel/air mixture results in reduced heat losses from reactions. Thus, the flammability limits of that gas mixture broaden. Figure 10 shows how the flammability limits of methane broaden as initial gas temperature increases. Gas mixtures falling in the area between the upper and lower limit lines are flammable.

Lowering atmospheric pressure has a minimal effect on the flammability limits of fuel/air mixtures until a very low pressure has been achieved. Figure 11 shows the effect of lowering pressure on natural gas/air mixture flammability limits. Until the gas pressure is reduced below 3 psia, the flammability limits are only slightly affected, although the total heat release will be

[17] For atmospheric pressure and room temperature. Lewis, B., and G. von Elbe, *Combustion, Flames and Explosions of Gases*, 2nd Edition, Academic Press, New York, 1961.

reduced proportionately with the air pressure. Since passenger aircraft cannot use depressurization as a means to fight fires, flammability limits are expected to be similar to sea level values.

5.3 Fire Suppression Systems

An aircraft cargo hold Class C suppression system consists of three major components:

- A detection system to alert the crew of a fire while it is still in its early stages
- A suppressant discharge system that releases Halon 1301 into the cargo hold
- A flame resistant cargo liner that prevents fresh air from reaching the fire and acts to contain the fire, protecting surrounding equipment from high temperatures, and preventing smoke from entering the passenger cabin.

5.4 Detection Systems

The FAA currently requires that cargo hold detection systems activate within 1 minute of the start of a small smoldering fire, such as a single suitcase fire.[18] The FAA makes no distinction as to how the fire is to be detected (e.g. via smoke or fire sensing). However, detection is generally accomplished through an optical smoke obscuration technique. False alarms are typically minimized by requiring two detectors in a compartment to activate before the crew is signaled.[10]

5.5 Halon 1301 Systems

Although aviation regulations do not specifically require Halon 1301, years of widespread use and proven effectiveness on different types of fires has resulted in its acceptance as the standard agent for cargo hold fire protection.[19] Halon 1301 is the least toxic of the Halon fire suppressants and is considered to have superior fire extinguishing characteristics. In particular, it rapidly knocks down flaming combustion, has a penetrating vapor that can flow around baffles and obstructions, leaves no residue, is non-corrosive, requires small storage volumes, is non-conductive, and is colorless, which prevents the generation of false fire alarms by obscuration.

Halon 1301 (bromotrifluoromethane) is a methane derivative. The bromine atom confers strong fire suppressant properties, while the fluorine atoms confer stability to the molecule and reduce its toxicity. Bromine atoms interfere with the free radical and chain branching reactions that are important in combustion.

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[18] FAR 25.858

[19] Blake, D., "Status of the Development of a Minimum Performance Standard for Halon Replacement Agents in Aircraft Cargo Compartments," *FAA Fire Safety Section*, International Aircraft Fire and Cabin Safety Research Conference, Nov 16-20, 1998.

Halon 1301 is generally considered very effective for electrical fires (Class C fires[20]), flammable liquid and gas fires (Class B fires[21]), and surface-burning flammable solid (such as thermoplastic) fires. However, Halon 1301 has minimal effectiveness on reactive metals, rapid oxidizers, and deep-seated Class A fires.[22] Halon 1301 is minimally effective on deep-seated Class A fires because it works by interfering with the chemical reactions that create flames; it does not cool the fuel feeding the fire. Thus, while Halon 1301 can extinguish the flaming portion of a Class A fire, the glowing deep-seated portion of the fire can continue to smolder and spread at a reduced rate. In aircraft cargo hold applications, it is expected that during the suppression period, the contents of the cargo hold can continue to smolder, and the hold may remain hot, though flames will not be present.

5.5.1 System Design

Halon 1301 cargo hold suppression systems are designed to produce an initial discharge that will result in an average 5% Halon concentration in an empty cargo hold. After this initial burst, which is designed to knock down flaming combustion, the system must maintain a 3% Halon 1301 concentration for the remainder of the flight, in order to continuously suppress the fire and prevent re-ignition of flaming combustion.[10]

Halon 1301 is typically stored in banks of spherical bottles inside cargo compartments. The amount of Halon 1301 carried by any aircraft will depend upon cargo compartment size and allowable flight time from the nearest airport. For example, a 747 will carry between 270 and 1214 lbs of Halon 1301 for use in the cargo compartments, while a 757 will carry between 45 and 66 lbs.[23]

Typically, Halon 1301 is initially discharged as an unmetered burst from a high rate bottle. Since the system is designed to produce a 5% mixture of Halon in an empty cargo hold, typical resulting initial concentrations will be higher, and depend upon the volume of cargo contained in the hold. The subsequent Halon releases can be accomplished by the firing of backup bottles at some pre-arranged time intervals, or by using a metered release system. In either case, the systems are set to release additional Halon once the original concentration has decayed below 3%.

5.5.2 Halon 1301 Suppression

The strong effect of Halon addition can be seen upon examining the flammability limits of fuel/air/Halon mixtures, and comparing them with the flammability limits of fuel/air/inert diluent mixtures. Figure 12 shows that when small quantities of Halon are added to a fuel/air mixture, they narrow the range in which that mixture is flammable. Figure 12 also shows that

[20] NFPA 10, "Standard for Portable Fire Extinguishers," defines Class C fires as fires involving energized electrical equipment.

[20] NFPA 10, "Standard for Portable Fire Extinguishers," defines Class B fires as fires involving flammable liquids and gases.

[22] NFPA 10, "Standard for Portable Fire Extinguishers," defines Class A fires as fires involving ordinary combustible materials such as paper, wood, cloth, and many plastics.

[23] "Halon Replacement in Civil Aviation," *Airliner Magazine*, April-June 1997, pp. 40-49.

Halon is far more effective at narrowing the flammable range than an inert diluent. If sufficient Halon is added, the flammable range of a mixture, even at an elevated temperature, is eliminated and the mixture cannot be ignited.

Table 5 shows the average percent by volume of agent in air required to extinguish a flame. It also shows the design concentrations for a total flooding system required to suppress flaming combustion. The design concentrations for flame extinguishment include an added safety factor over the required concentrations. These design recommendations are approximately 5% for most fuels, which is also the minimum initial design concentration for aircraft cargo hold Halon systems.

Table 5: Minimum required and design volume percentage of Halon 1301 at 25 C that will prevent burning of various vapors

Fuel	Volume % Halon 1301 in air required for flame extinguishment[24]	Design concentrations for flame extinguishments (volume % Halon)[25]
Methane	3.1	5.0
Propane	4.3	5.2
n-Heptane	4.1	5.0
Ethylene	6.8	8.2
Acetone	3.3	5.0
Benzene	3.3	5.0
Ethanol	3.8	5.0
Plastics	4 – 6	

5.6 Cargo Hold Liner

The cargo hold liner is designed to aid fire suppression by reducing the inflow of fresh oxygen to a fire, by containing the fire, and by confining the released Halon 1301 to the vicinity of the fire. In addition, the liner is designed to insulate surrounding structure, equipment, and passenger spaces from the heat of a cargo hold fire. The liner itself is fire resistant, so that it will not readily act as an added source of fuel.

Once a fire begins, it consumes oxygen and releases primarily non-flammable combustion products such as water vapor and carbon dioxide. Since combustion products are hot, they rise to the ceiling of a compartment. This results in the creation of a temperature gradient within a

[24] Taylor, G.M., "Halogenated Agents and Systems," Section 6, Chapter 18, *Fire Protection Handbook*, 18th ed., National Fire Protection Association, 1997.
[25] Grant, C.C., "Halon Design Calculations," Section 4, Chapter 6, *SFPE Handbook of Fire Protection Engineering*, 2nd ed., Society of Fire Protection Engineers, 1995.

compartment, where the highest temperatures are found near the ceiling and the lowest temperatures are found near the floor.

If oxygen becomes limited, or flaming combustion is prevented due to the action of Halon, the resulting smoldering of Class A combustibles (paper, cardboard, plastics, textiles) will produce partially oxidized products as well as pyrolysis gases, such as carbon monoxide, oxygenated organics, saturated and unsaturated hydrocarbons, aromatic hydrocarbons, and soot. These gases are hot and combustible, and will also rise to the ceiling of a compartment, resulting in a temperature gradient. A slow, confined, smoldering process can fill a compartment with combustible gases to the point that they are above the UFL of the mixture, and will only ignite if diluted with air. The addition of fuel compounds (from cell venting, for example) to a mixture that is above its UFL will not increase the possibility that a flame will be able to propagate. Rather, it will make the mixture more fuel rich and shift it further from the flammable range.

Smoldering consumes both fuel and oxygen at a slower rate than flaming combustion and releases less heat than a flaming combustion process. Cargo hold ceiling liners are designed to withstand the temperatures produced by the smoldering of cargo for long periods, but they are not capable of withstanding long-term exposure to flaming combustion. A liner breach can result in the ventilation of a compartment, with the resulting addition of oxygen to a smoldering fire causing acceleration and transition to flaming combustion, a reduction in the compartment Halon concentration (which reduces its effectiveness as a flame suppressant), and the ignition of collected incomplete combustion products.

6 FAA Cargo Hold Fire Testing

The FAA has conducted a variety of ground-based, full-scale cargo fire tests to explore the cargo fire hazard, and examine the relative effectiveness of various cargo hold components. As part of their testing, the FAA typically measured ceiling temperatures, oxygen concentrations, and Halon concentrations.

6.1 FAA Cargo Hold Fire Testing

6.1.1 LD-3 Container Tests, 1983

In 1983, the FAA conducted fire tests in LD-3 containers (150 ft^3) to assess their fire containment capabilities.[26] They conducted a total of 10 tests on a variety of LD-3 container styles:

- Rigid fiberglass containers with both fiberglass and neoprene/nylon doors
- Aluminum containers with both aluminum and vinyl doors
- An aluminum container with an aluminum door and holes cut in the side of the container
- A high-density polyethylene container with an aluminum door.

The FAA loaded the containers approximately 70% full with cardboard boxes filled with polyurethane foam, and started the fire by igniting a box filled with newspaper and foam. The FAA found that as long as the container door was not compromised, which only occurred with vinyl or neoprene/nylon doors, oxygen starvation of the fire would result only in smoldering. However, if burn-through of the door occurred, then the resulting oxygen addition would result in flaming re-ignition of the fire.

6.1.2 Simulated Class D Compartment Tests, 1983

In 1983, the FAA conducted fire tests in a simulated 640 ft^3 Class D cargo compartment.[7] They conducted the tests to assess the fire-spread consequences of various ceiling liner materials, cargo loading configurations, air leakage rates, and fire sources. The fires were started in unclaimed luggage stacked in the compartment center. The fire was ignited approximately 18 inches below the ceiling liner. The remainder of the compartment was loaded with cardboard boxes to achieve a 50% load by volume. The FAA found that a fiberglass/polyester ceiling liner

[26] Blake, David R., *Evaluation of Fire Containment of LD-3 Cargo Containers*, DOT/FAA/CT-TN83/38, FAA Technical Center, October 1983.

performed better from the standpoint of burn-through resistance than a Nomex/epoxy liner. The FAA also found that forced ventilation enhanced fire growth and severity.

6.1.3 Simulated Class C Compartment Tests, 1985

In 1985, the FAA conducted 23 fire tests in a simulated 2357 ft^3 Class C cargo compartment.[6] They conducted tests using various lining materials, fire sources, loading configurations, and smoke detectors in order to assess the ability of these compartments and systems to control cargo fires. The test article was the aft section of a DC-10 fuselage. The FAA removed the bulkhead between the center cargo compartment and the rear bulk cargo compartment to simulate a single large lower lobe compartment. The airflow surrounding the cargo compartment was simulated by forcing 1850 CFM of air through the test article. This provided approximately one air change every four minutes in the test article in entirety. A leakage rate of 80 CFM was imposed on the cargo compartment. A pet air system was simulated by attaching a ventilation system to the cargo compartment, capable of forcing 260 CFM of air into that compartment.

A Halon 1301 suppression system was installed in the compartment. It consisted of three bottles, two of which were fired initially to provide at a minimum a 5% Halon concentration in the cargo hold. The backup bottle was fired 54 minutes after the initial discharge.

Partial loading of the cargo hold was simulated by filling 40% of the volume with cardboard boxes packed with foam. Fires were initiated among suitcases filled with clothing, or among boxes filled with packing foam and newspaper. The fires were started by ignition of matches either inside a cloth gym bag filled with newspaper, rags, and in some scenarios bags of flammable liquids, or in boxes filled with foam and newspaper. The pet air system was run until two smoke detectors signaled a fire. After a specified delay time, the pet air system was shut down and Halon was discharged into the compartment.

In general, the FAA found that a fiberglass liner performed significantly better than a Kevlar/epoxy liner by exhibiting higher burn-through resistance, lower Halon leakage, and lower smoke leakage. In two of the tests, fires were started inside LD-3 containers. In one case, the fire burned through the container at the same time that the cargo hold sensors activated, and was subsequently suppressed by the Halon.

6.1.4 FAA Tests, 1998

In 1998, the FAA reported the results of a set of cargo hold fire tests exploring three areas of interest: the effectiveness of two Halon 1301 alternatives, the effectiveness of Halon 1301 on fires involving rupturing aerosol cans, and the effectiveness of Halon 1301 on fires involving oxygen generators.[27] Halon 1301 testing, HFC-125 testing, and some oxygen canister testing was conducted in a 2357 ft^3 cargo compartment of a DC-10 test article, instrumented to record ceiling temperatures, oxygen concentrations, and suppression agent concentrations. Water mist

[27] Blake, David, T. Marker, R. Hill, J. Reinhardt, and C. Sarkos, *Cargo Compartment Fire Protection in Large Commercial Transport Aircraft*, DOT/FAA/AR-TN98/32, U.S. Dept. of Transportation, FAA, July 1998.

testing, aerosol can simulator testing, and some oxygen canister testing was conducted in a B-727 aft cargo compartment test article (550 ft3) instrumented to record ceiling temperatures.

Tests to compare the effectiveness of Halon 1301 with the effectiveness of HFC-125 on a bulk loaded cargo fire were conducted with a 30% full cargo hold. The fire load consisted of cardboard boxes filled with shredded paper. Halon 1301 effectively suppressed the fire during a 90-minute test. However, during one test with HF-125, an ignition of the combustible gases occurred in the smoke layer above the boxes when this agent's concentration was low.

Aerosol can simulator testing was conducted to develop a simulator that would repeatedly produce a flammable vapor cloud as would occur during an aerosol can rupture event. The FAA had previously observed that some cans would release their contents in a slow venting process, resulting in a "blowtorch" event, which was significantly milder than a "vapor cloud explosion" event. The aerosol can simulator was developed to reliably reproduce the "vapor cloud" condition. The FAA observed that a 6.5% Halon concentration effectively inerted the B-727 cargo compartment. The aerosol can simulator was also tested inside LD-3 containers, which the FAA observed were successfully inerted with only 1% Halon concentration.

Oxygen canister tests were conducted to determine if Halon 1301 would have a beneficial effect on a fire involving oxygen generators. The FAA observed that if Halon was used, ceiling temperatures were reduced, and that depending upon the number of generators activated, an oxygen-fed fire might be successfully suppressed.

6.2 Measured Ceiling Temperatures

6.2.1 LD-3 Container Tests, 1983

The FAA reported maximum ceiling temperatures in a range of 1200 F -1500 F (649 C– 816 C) immediately after ignition. If burn-through of the door did not occur, these peak temperatures quickly decreased within two to four minutes to a range of 200 F – 600 F (93 C –316 C) (Figures 14 and 15).

6.2.2 Simulated Class D Compartment Tests, 1983

In these tests, the FAA reported a maximum ceiling temperature of 1800 F (982 C) under forced air conditions during tests simulating an operating "pet air system." Similar tests conducted without forced air resulted in maximum ceiling temperatures below 1250 F (677 C) (Figure 15).

6.2.3 Simulated Class C Compartment Tests, 1985

In these tests, the FAA reported a maximum ceiling temperature of approximately 1700 F (927 C) that dropped within five minutes to less than 300 F (149 C) (Figure 16). The drop in temperature corresponded to the discharge of Halon into the compartment.

6.2.4 FAA Tests, 1998

During 90-minute Halon 1301 bulk loaded fire tests, the FAA observed a maximum ceiling temperature of approximately 450 F (232 C) (Figure 17). During the oxygen canister tests, the FAA observed maximum ceiling temperatures below 500 F (260 C). The ceiling temperatures eventually dropped below 250 F (121 C) (Figure 18).

The reported ceiling temperatures observed during FAA testing during slow smoldering of a suppressed cargo hold fire are sufficiently high to cause lithium-ion cell venting, if a cell were exposed for a sufficient length of time. The length of time required would be highly dependant upon the heat capacity of the cell itself, and the heat capacities and insulating properties of the packaging surrounding the cell. In the case of a palletized bulk shipment of cells or battery packs, one would expect that the cells near the top of the pallet would be most susceptible, and would heat to a venting temperature only after the cardboard or fiberboard packaging surrounding them had been heated, and the cells were no longer transferring away sufficient heat to cells or battery packs deeper within the pallet. In the case of a containerized shipment of cells subjected to an external fire, the situation would be similar, except that the container walls would first have to be heated prior to their transferring heat to packaging materials.

6.3 Measured Oxygen Concentrations

6.3.1 LD-3 Container Tests, 1983

In these tests, the FAA reported oxygen concentrations that dropped from 21% to below 10% within two to eight minutes of ignition, if burn-through of the container door did not occur (Figure 19).

6.3.2 Simulated Class D Compartment Tests, 1983

In these tests, the FAA reported oxygen concentrations that dropped from 21% to below 10% within eight minutes of ignition when a fiberglass ceiling liner was used. Oxygen concentrations dropped below 13% when a Nomex ceiling liner was used (Figure 20).

6.3.3 FAA Tests, 1998

During 90-minute Halon 1301 bulk loaded fire tests, the FAA reported oxygen concentrations that dropped to 10%-15% (Figure 17).

FAA testing has shown that shortly after a fire begins in a cargo hold, the oxygen concentration in the hold begins to drop. This drop occurs because oxygen is consumed in the combustion process, while carbon dioxide and water vapor are formed. If Halon is released into the compartment, it will displace and dilute the oxygen. In addition, since combustion products are warm and begin to heat the compartment atmosphere, expansion of the compartment gases will tend to force compartment gases out of the compartment leak points, rather than allowing fresh air into the compartment. These effects significantly reduce the possibility that a cargo hold atmosphere will be within its flammable range. If flammable gases such as the products of incomplete combustion resulting from smoldering, the propellant gases from ruptured aerosol cans, or the vent gases from lithium-ion cells are added to the cargo hold gas mixture, the atmosphere will remain resistant to ignition.

6.4 Measured Halon Concentrations

6.4.1 Simulated Class C Compartment Tests, 1985

In these tests, the FAA reported a maximum Halon concentration of approximately 8% that decayed in a linear manner to 3% over the course of 40 minutes in a fiberglass-lined compartment (Figure 21).

6.4.2 FAA Tests, 1998

During 90-minute Halon 1301 bulk loaded fire tests, the FAA reported Halon concentrations that were initially above 5%, and were then metered to maintain a 3% concentration (Figure 17).

The FAA testing showed that shortly after a fire is detected in a cargo hold, the hold is flooded with Halon 1301 suppressant, which significantly reduces the possibility that a flame will be able to propagate through the cargo hold atmosphere. The Halon does not typically extinguish the fire; rather, it suppresses flaming combustion while smoldering continues. The smoldering process will continue to produce flammable gaseous products of incomplete combustion. However, after Halon is released, the compartment atmosphere is resistant to flame propagation despite the addition of such flammable gases (e.g. the products of incomplete combustion and smoldering, the propellants from ruptured aerosol cans, or the vent gases from lithium-ion cells).

7 Conclusions

Based on the reviewed information, Exponent has concluded the following:

1. A cargo hold fire could produce temperatures near the ceiling of the hold that might cause lithium-ion cells to vent, if they were subjected to these temperatures for a sufficient length of time. However, the heating of lithium-ion cells would be retarded by the presence of surrounding packaging and the heat capacities of the cells themselves. The initial rate of cell heating would be highly dependent upon packaging details.

2. Pallets of lithium-ion cells or batteries are shipped in large Class C cargo holds (on passenger aircraft) where palletization and containerization, rather than bulk loading, of cargo and baggage is typical. Baggage and cargo are not typically mixed on pallets or in containers; rather, they are segregated to allow for efficient ground handling. Therefore, it is unlikely that a pallet of lithium-ion cells or battery packs would be subjected to direct flame impingement from an article of burning passenger luggage during the early initiation stage of a fire. Thus, lithium-ion cells or battery packs would be unlikely to vent prior to a cargo hold fire being detected and Halon 1301 being discharged.

3. Shortly after a fire is detected in a Class C cargo hold, the hold is flooded with Halon 1301 suppressant, which significantly reduces the possibility that a flame will be able to propagate through the cargo hold atmosphere. After Halon is released, the compartment atmosphere is resistant to flame propagation despite the addition of flammable gases such as the products of incomplete combustion resulting from smoldering, the propellants from ruptured aerosol cans, or the vent gases from lithium-ion cells.

4. Shortly after a fire begins in a cargo hold, the oxygen concentration in the hold begins to drop, and carbon dioxide and water concentrations resulting from the combustion process begin to increase. These effects significantly reduce the possibility that a flame will be able to propagate through the cargo hold atmosphere. After the oxygen concentration drops by a sufficient amount, the compartment atmosphere is resistant to flame propagation despite the addition of flammable gases such as the products of incomplete combustion resulting from smoldering, the propellants from ruptured aerosol cans, or the vent gases from lithium-ion cells as long as the compartment walls are not breached and air is not added.

5. Smoldering Class A combustibles such as paper, cardboard, plastics, and textiles will fill a closed compartment with flammable products of incomplete combustion. Without addition of oxygen, the resulting mixture will be above

the UFL, such that the addition of fuel compounds (from cell venting or release of aerosol propellants) will not increase the possibility that a flame will be able to propagate through the cargo hold atmosphere. Rather, the addition of fuel will make the mixture more fuel rich and move it further from the flammable range.

6. Lithium-ion battery cells are specifically designed to vent, rather than rupture, upon overheating. The FAA aerosol can simulator is designed to mimic the effect of an aerosol can rupture, and as such is considered an aggressive test for suppression of a luggage fire that interacts with an aerosol can. The FAA is particularly concerned with aerosol can rupture early in the initiation of a fire, prior to the fire's detection or the deployment of Halon1301. Aerosol can simulator testing shows that once Halon has been released into a compartment, the propellant gas will not ignite.

These conclusions have been based upon information available in published literature and additional information may help to refine them. For example, Exponent could find no specific data on the flammability limits of lithium-ion vent gases or the flammability limits of vent gas/Halon 1301 mixtures, particularly at elevated initial temperatures. These flammability limits might be estimated from the published limits for individual species if the composition of the vent gases were to be measured. Total quantities of electrolyte that might vent could be estimated from data concerning the typical quantities, and packing dimensions of shipped cells and battery packs. An analysis of the thermal properties of packaging materials would allow an estimate for the length of time that a shipment of cells might be exposed to elevated cargo hold fire temperatures, prior to cell venting.

8 Figures

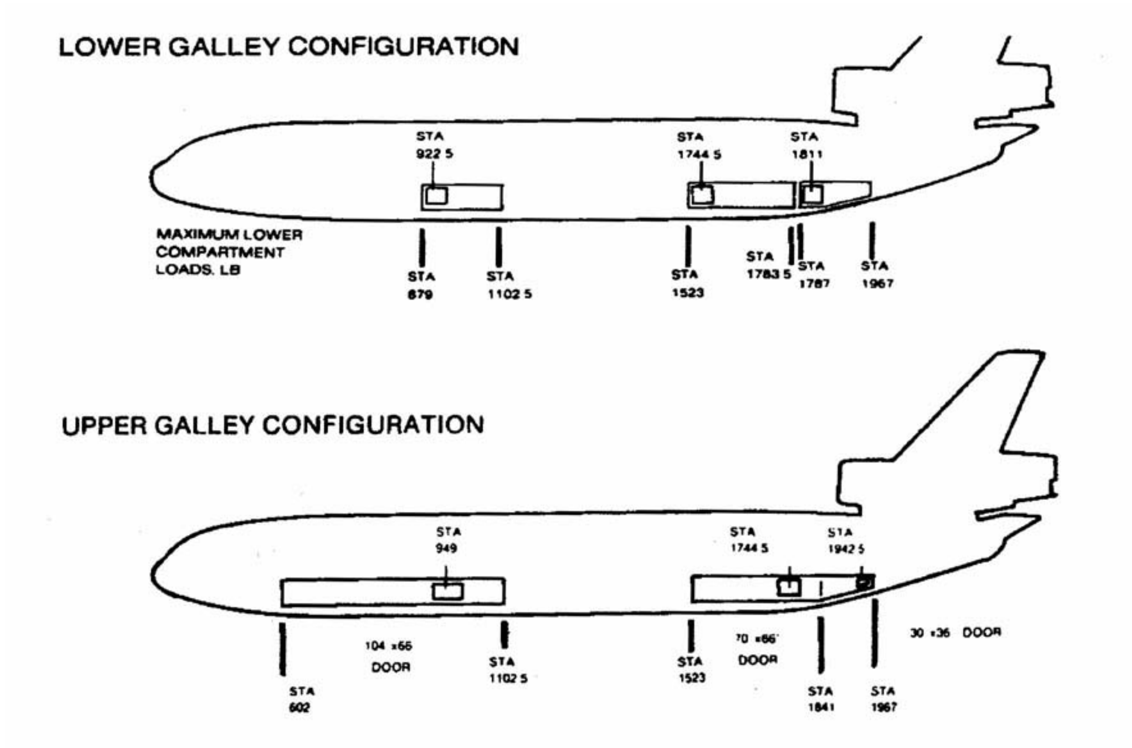


Figure 1. Cargo hold locations in a DC-10 aircraft (from AMC Pamphlet 55-41, Department of the Air Force, October 1992).

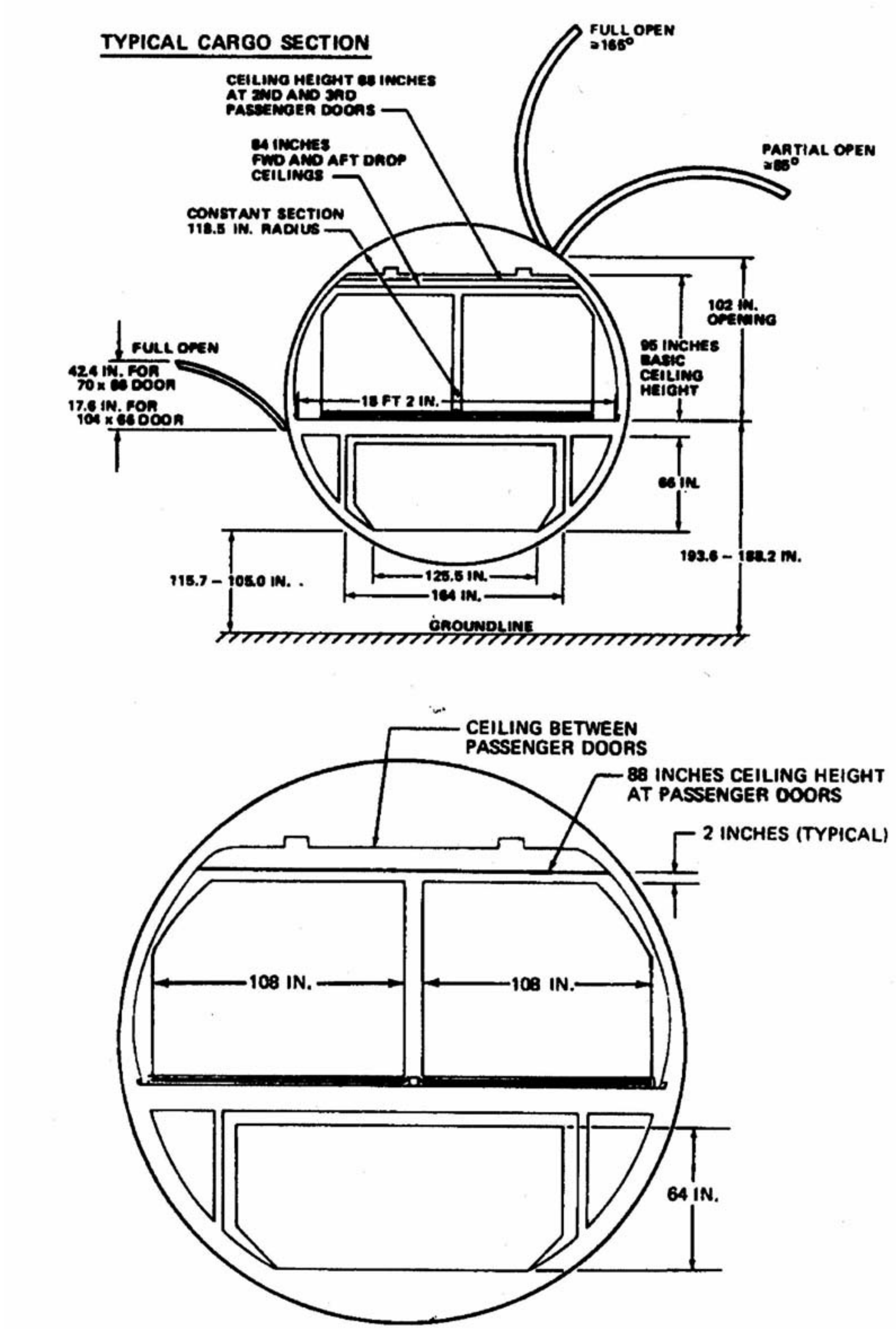


Figure 2. DC-10 cargo aircraft fuselage in cross section. On passenger aircraft, the upper deck is filled with seats rather than cargo containers (from AMC Pamphlet 55-41, Department of the Air Force, October 1992).

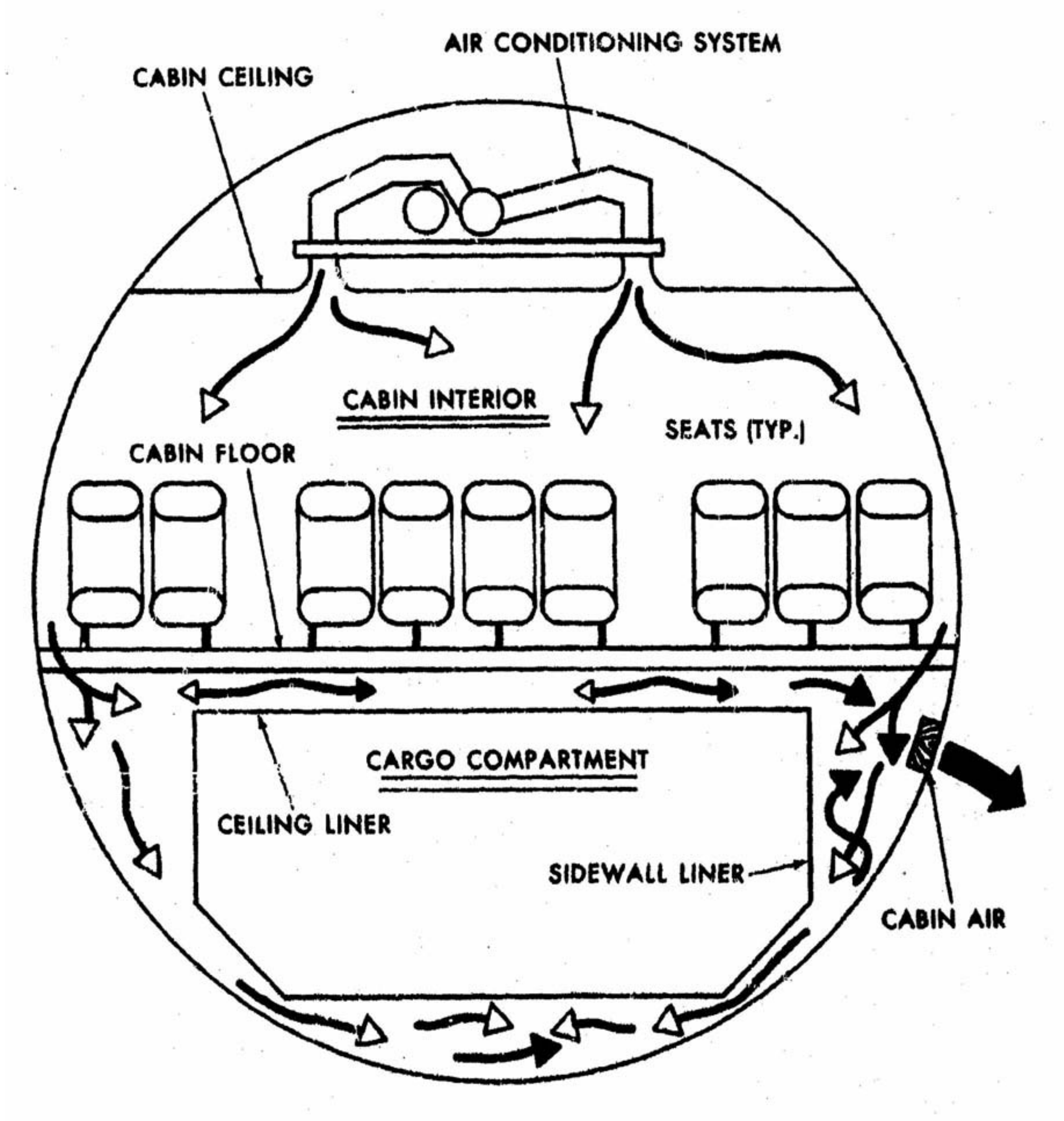


Figure 3. Typical airflow in a passenger aircraft (from Blake, D. R. and R. Hill, *Fire Containment Characteristics of Aircraft Class D Cargo Compartments*, DOT/FAA/82-156, FAA Technical Center, March 1983).

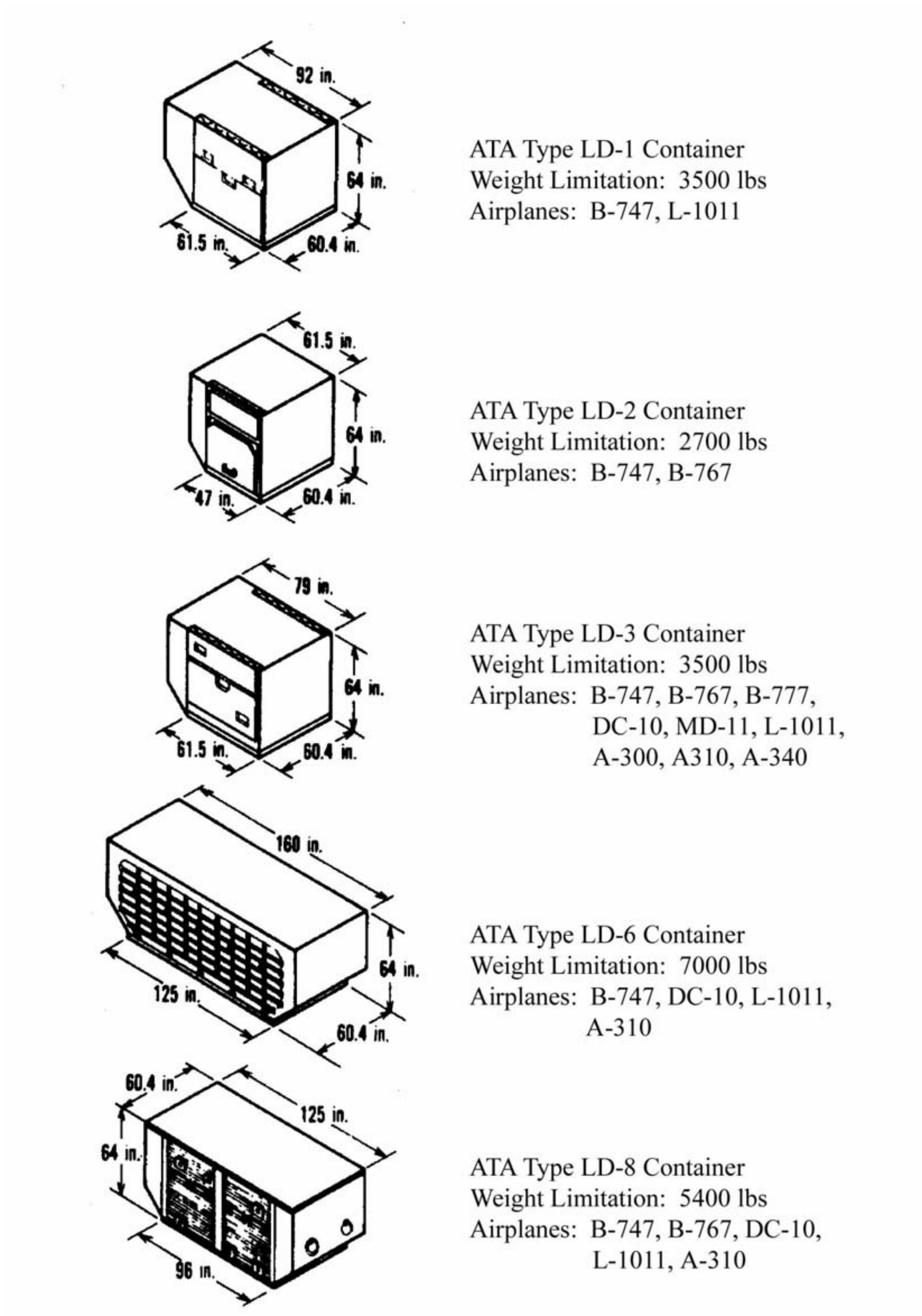


Figure 4. Typical lower lobe aircraft cargo containers (from AMC Pamphlet 55-41, Department of the Air Force, October 1992).

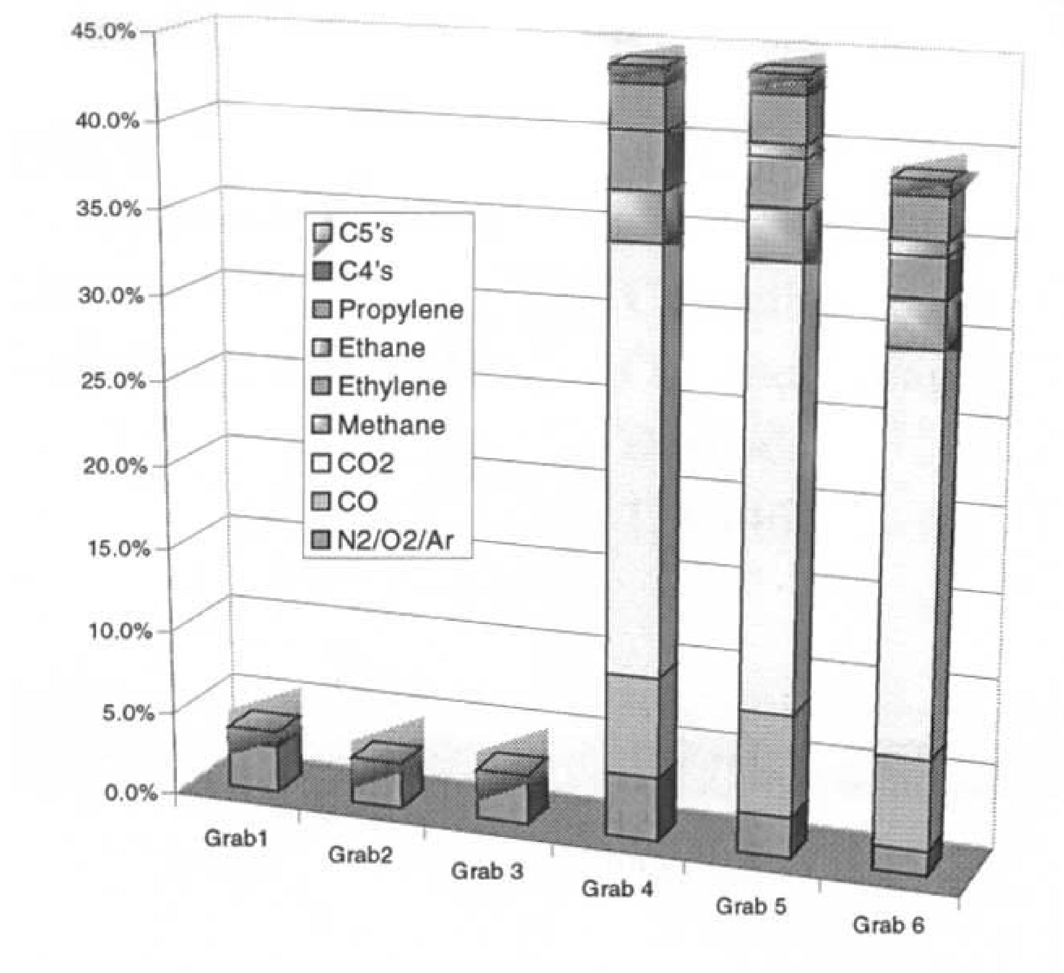
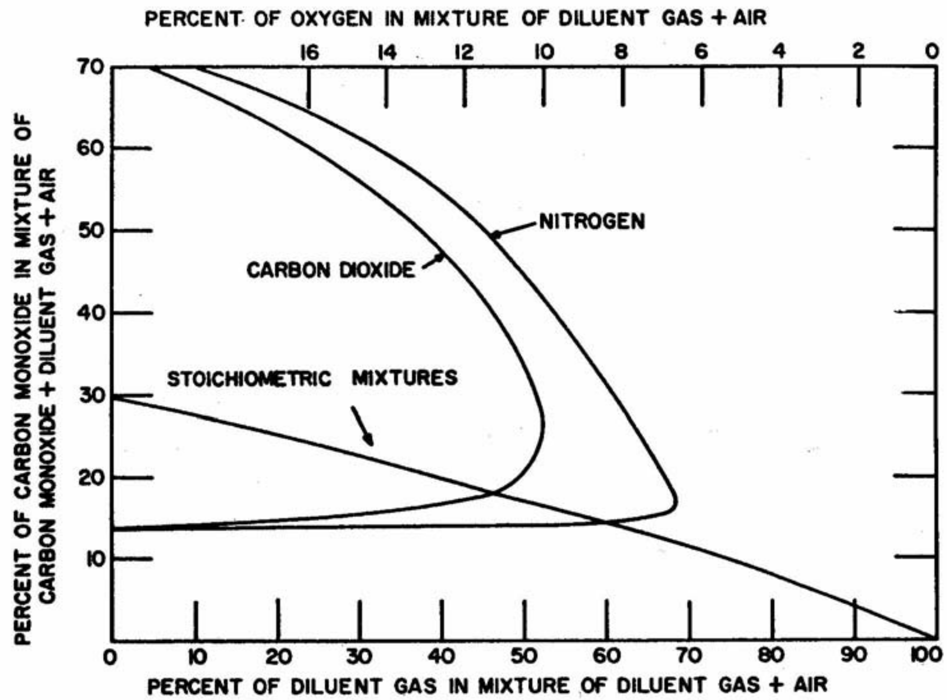
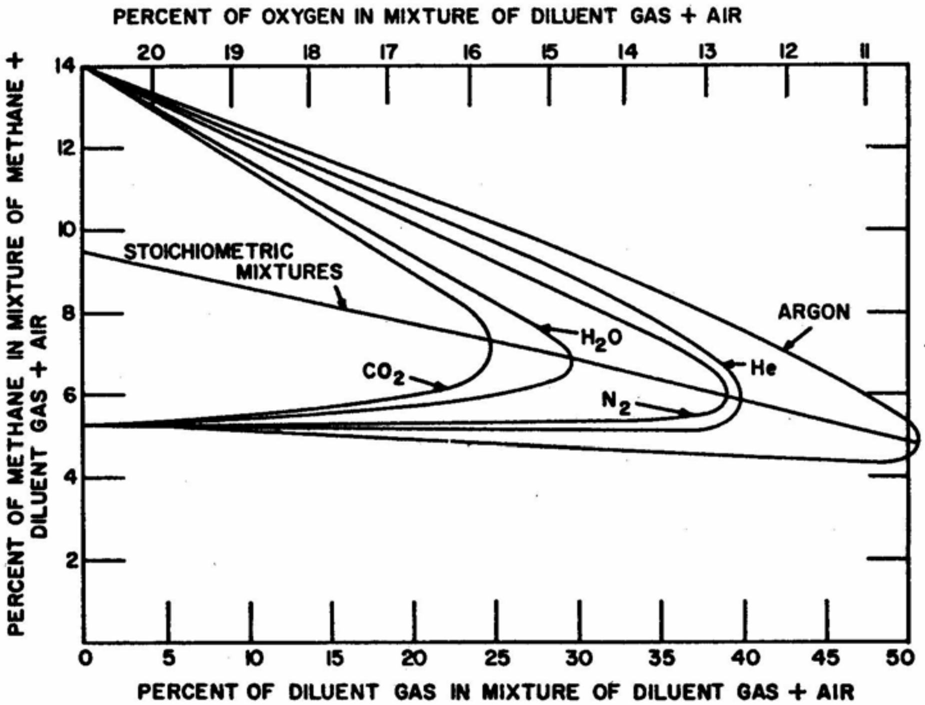


Figure 5. Lithium-ion vent gas sample analysis (from Crafts, C., T. Borek, and C. Mowry, "Safety Testing of 18650-Style Li-Ion Cells," Sandia National Laboratories, SAND2000-1454C, May 2000).



Limits of inflammability of carbon monoxide in air diluted with CO_2 and N_2. Mixtures saturated with water vapor at about 18°C. (Coward and Jones.) Room temperature and atmospheric pressure.

Figure 6. Effect of reduction of oxygen concentration due to dilution by nitrogen or carbon dioxide on the flammability limits of carbon monoxide (from Lewis, B. and G. von Elbe, *Combustion, Flames and Explosions of Gases*, 2nd Edition, Academic Press, New York, 1961).



Limits of inflammability of methane in air diluted with various inert gases. H_2O curve: Mixture temperature adjusted to yield required vapor pressure of water. Pressure, one atmosphere. (Coward and Jones.)

Figure 7. Effect of reduction of oxygen concentration due to dilution by various inert gases on the flammability limits of methane (from Lewis, B. and G. von Elbe, *Combustion, Flames and Explosions of Gases*, 2nd Edition, Academic Press, New York, 1961).

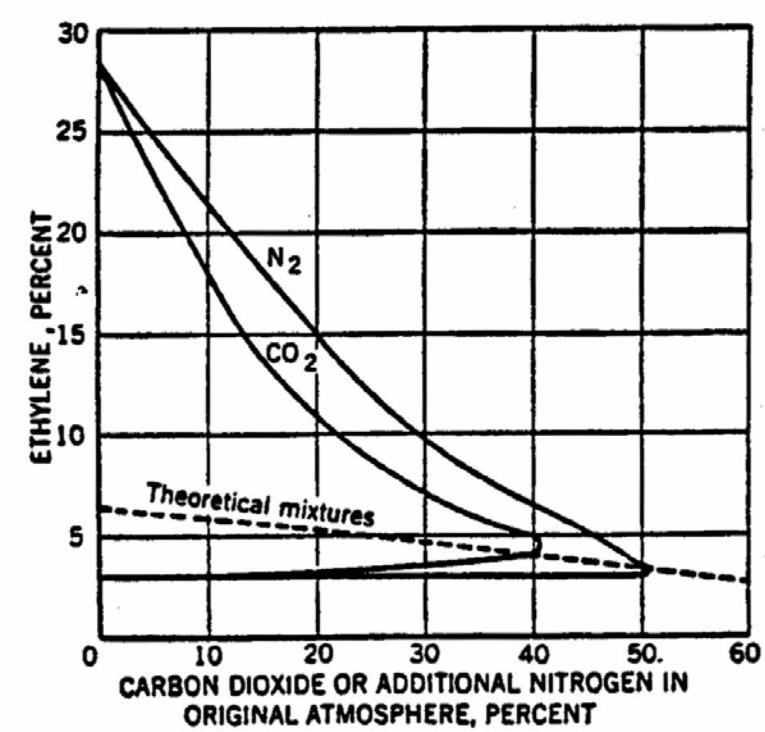


Figure 8. Effect of reduction of oxygen concentration due to dilution by carbon dioxide or nitrogen on the flammability limits of ethylene (from Coward, H.F. and W. Jones, *Limits of Flammability of Gases and Vapors*, Bulletin 503, US Bureau of Mines, 1952).

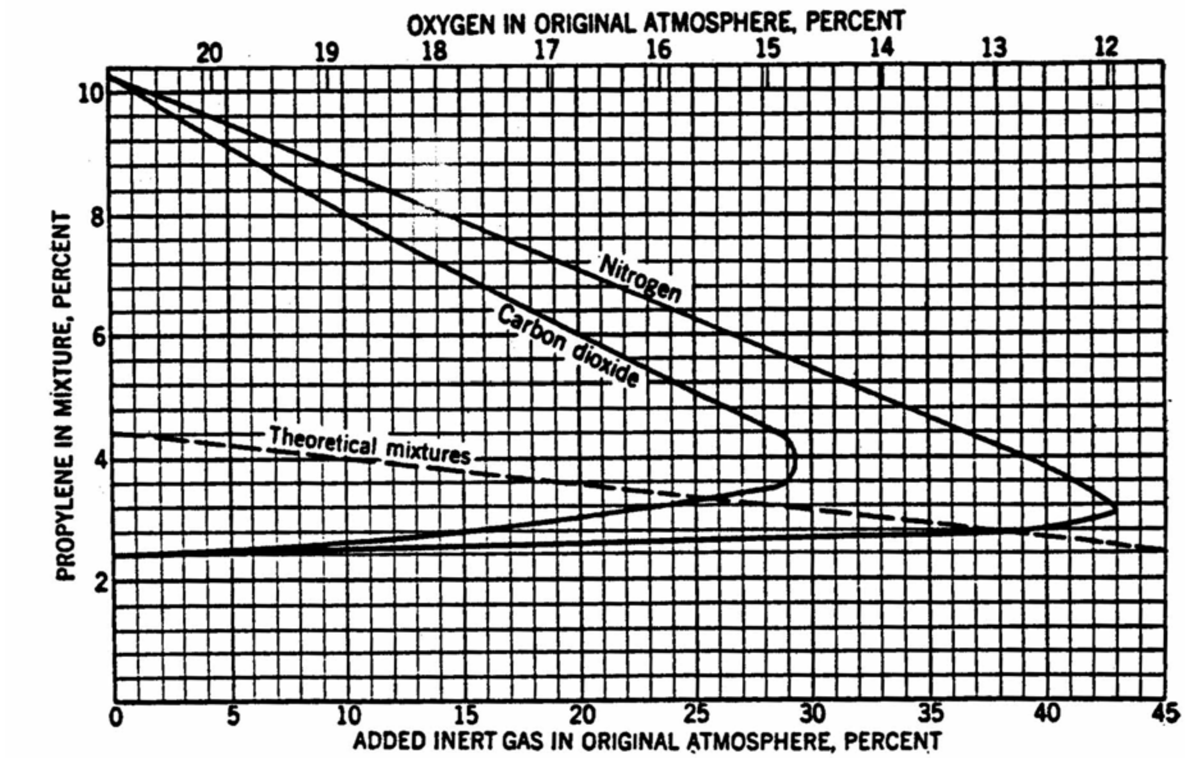


Figure 9. Effect of reduction of oxygen concentration due to dilution by carbon dioxide or nitrogen on the flammability limits of propylene (from Coward, H.F. and W. Jones, *Limits of Flammability of Gases and Vapors*, Bulletin 503, US Bureau of Mines, 1952).

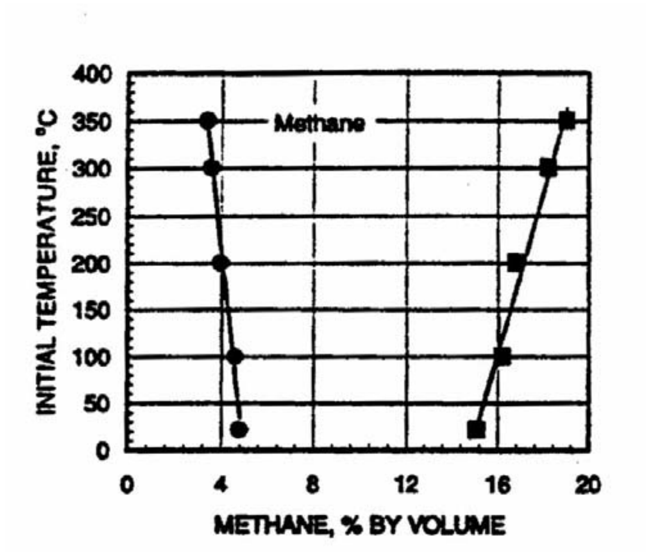


Figure 10. Effect of increasing temperature on the flammability limits of methane (from Wierzba, I. and B.B. Ale, "The Effect of Time of Exposure to Elevated Temperatures on the Flammability Limits of Some Common Gaseous Fuels in Air," *Journal of Eng. for Gas Turbines and Power*, Vol. 121, January 1999, pp. 74-79).

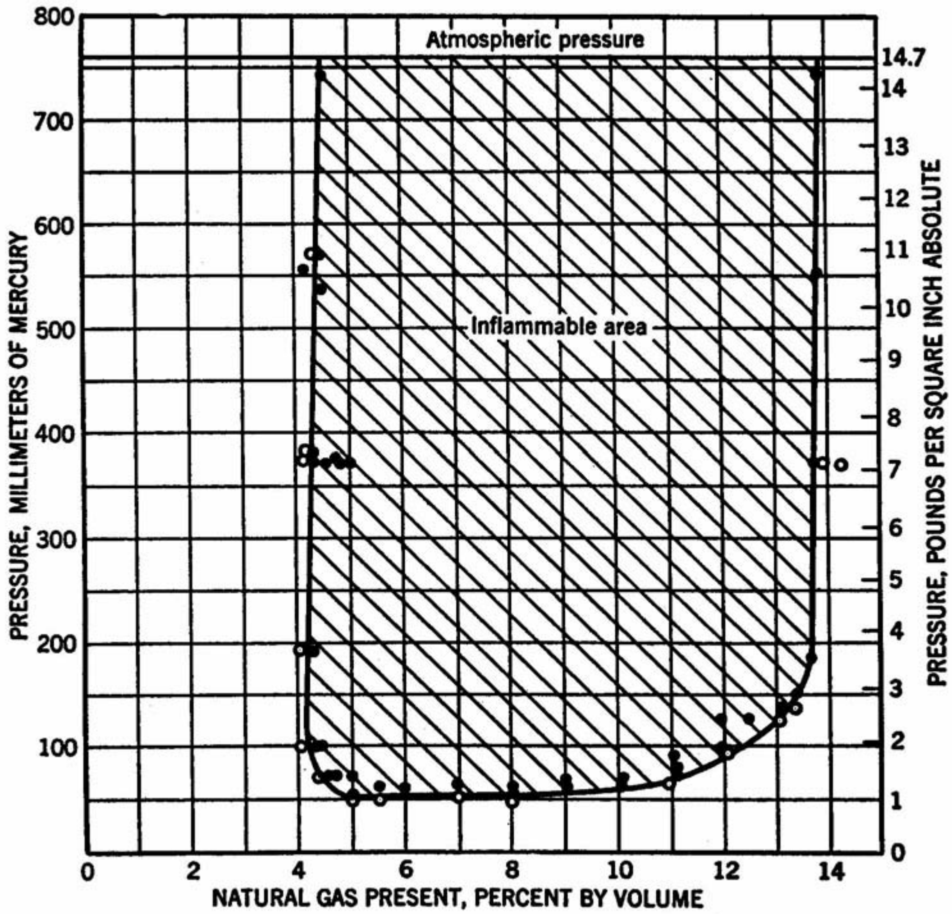


Figure 11. Effect of reduction of pressure below atmospheric on limits of flammability of natural gas/air mixtures (from Lewis, B., and G. von Elbe, *Combustion, Flames and Explosions of Gases*, 2nd Edition, Academic Press, New York, 1961).

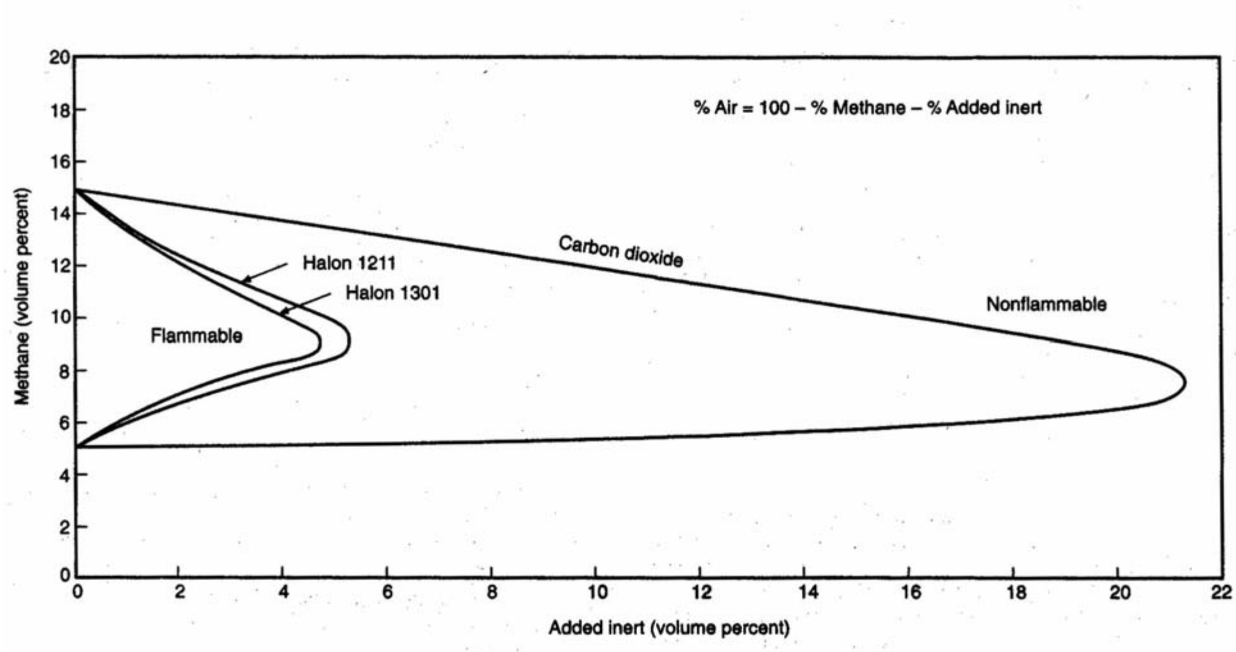


Figure 12. Effect of Halon addition on flammability of methane (from "Basics of Fire and Science," Section 1, Chapter 1, *Fire Protection Handbook*, 18th Edition, National Fire Protection Association, 1997).

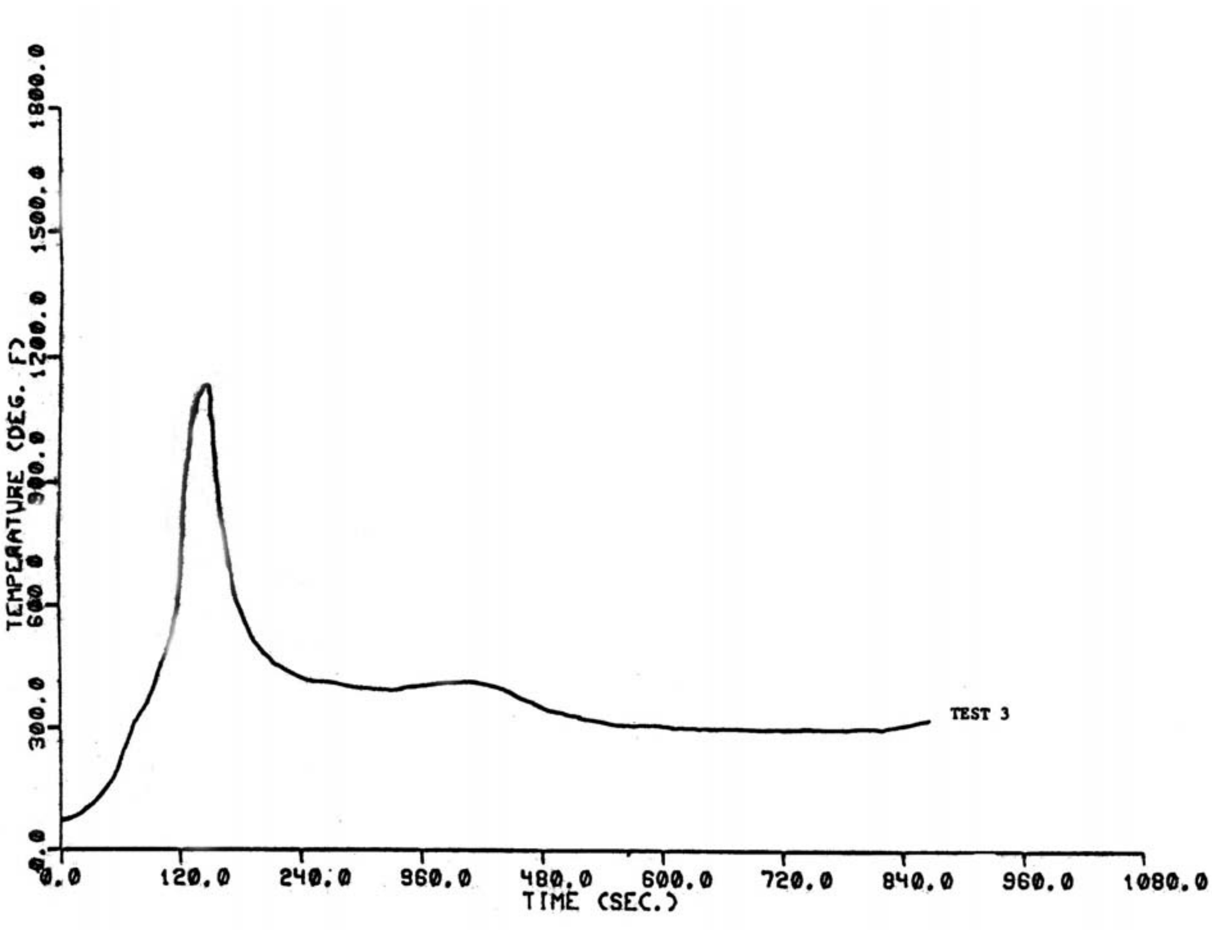


Figure 13. LD-3 container test ceiling temperature, rigid fiberglass container with neoprene/nylon door covering, burn time of 40 minutes, no damage to container (from Blake, David R., *Evaluation of Fire Containment of LD-3 Cargo Containers*, DOT/FAA/CT-TN83/38, FAA Technical Center, October 1983).

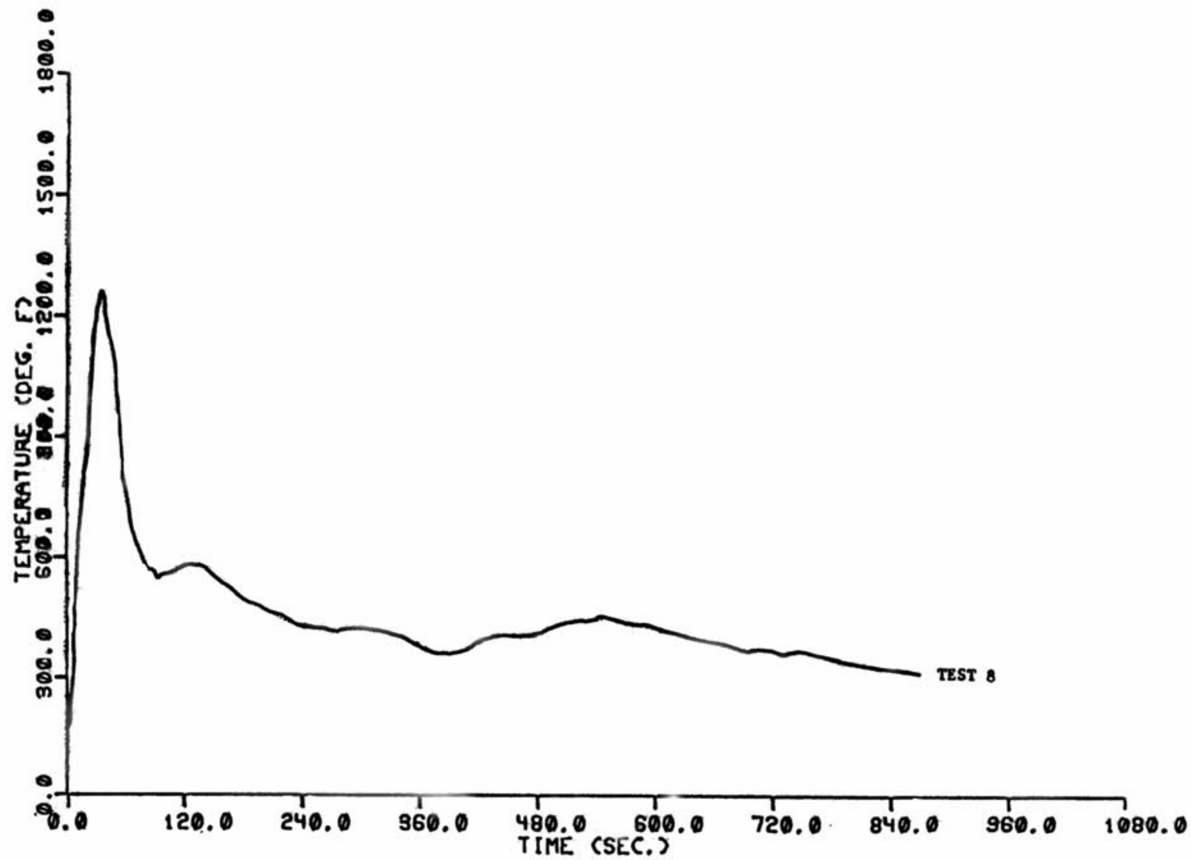


Figure 14. LD-3 container test ceiling temperature, aluminum container with aluminum doors, burn time of 18 minutes, no damage to container (from Blake, David R., *Evaluation of Fire Containment of LD-3 Cargo Containers*, DOT/FAA/CT-TN83/38, FAA Technical Center, October 1983).

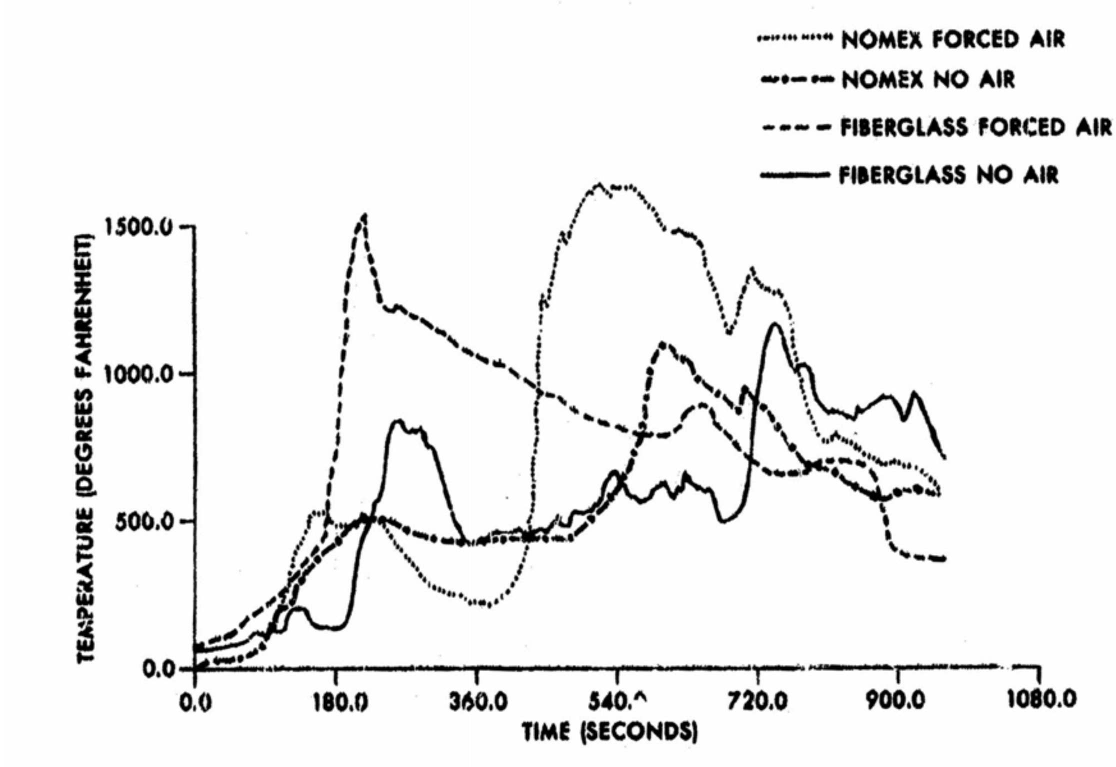


Figure 15. Ceiling temperatures measured during Class D compartment testing, under forced air conditions and without forced air with fiberglass and Nomex/epoxy ceiling liners (from Blake, David R. and Richard Hill, *Fire Containment Characteristics of Aircraft Class D Cargo Compartments*, DOT/FAA/82-156, FAA Technical Center, March 1983).

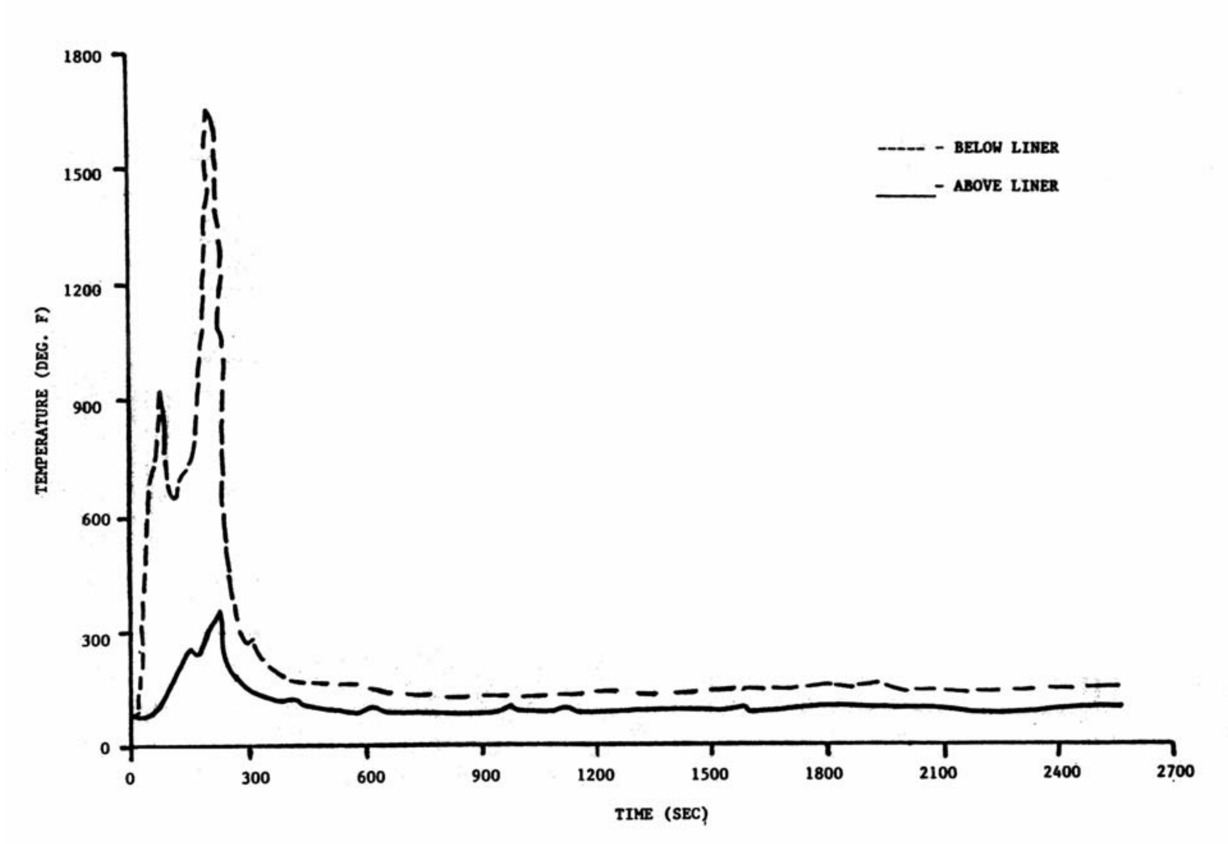


Figure 16. Class C compartment testing, temperature above and below a fiberglass ceiling liner (from Blake, David R., *Suppression and Control of Class C Cargo and Compartment Fires*, DOT/FAA/CT-84/21, U.S. Dept. of Transportation, FAA, February 1985.

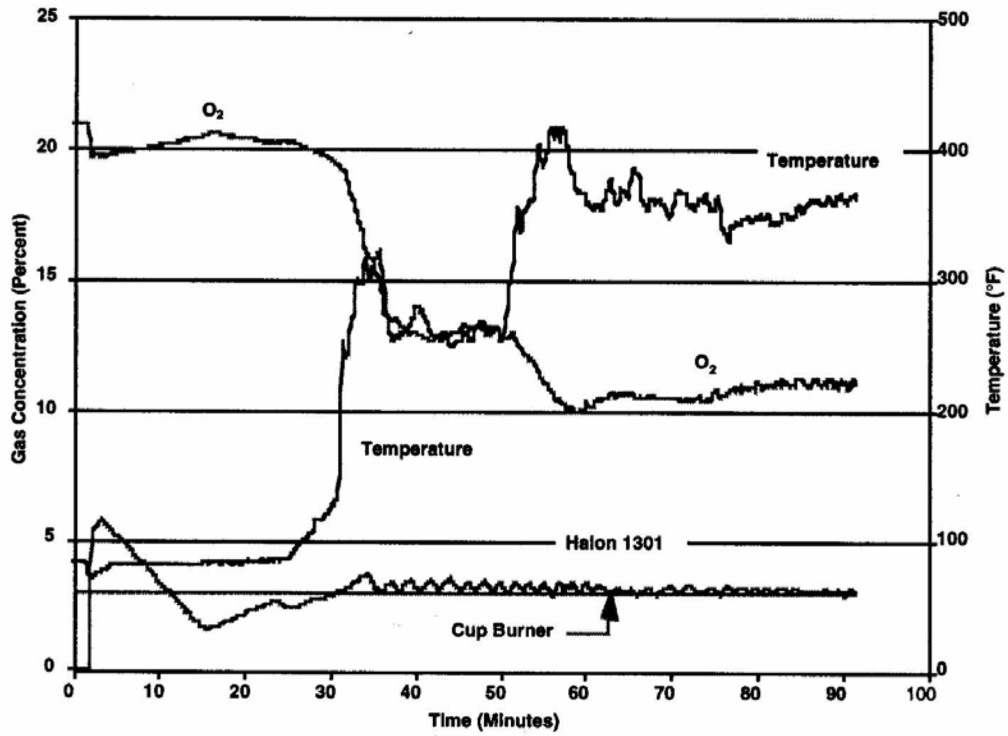


Figure 17. Temperature, oxygen concentration, and Halon 1301 concentration profiles in cargo compartment during bulk loaded fire suppression tests (from Blake, David, T. Marker, R. Hill, J. Reinhardt and C. Sarkos, *Cargo Compartment Fire Protection in Large Commercial Transport Aircraft*, DOT/FAA/AR-TN98/32, U.S. Dept. of Transportation, FAA, July 1998).

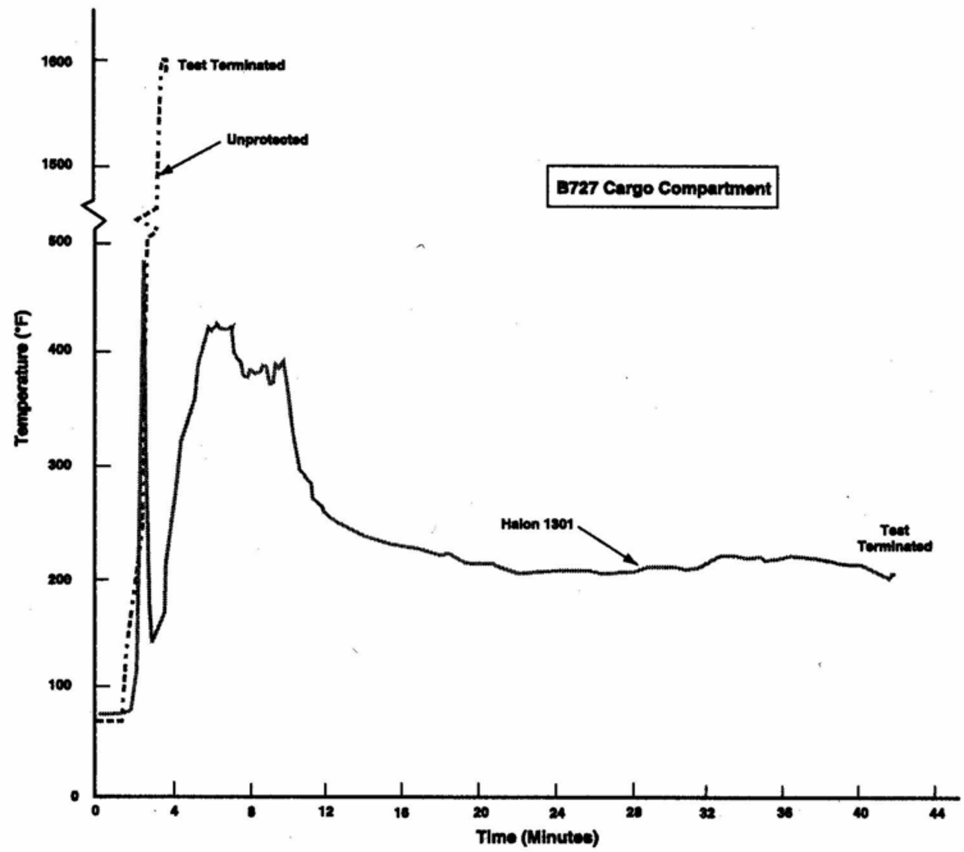


Figure 18. Comparison of ceiling temperatures during a cargo fire involving 12 oxygen canisters with Halon 1301 suppression and without suppression (from Blake, David, T. Marker, R. Hill, J. Reinhardt and C. Sarkos, *Cargo Compartment Fire Protection in Large Commercial Transport Aircraft*, DOT/FAA/AR-TN98/32, U.S. Dept. of Transportation, FAA, July 1998).

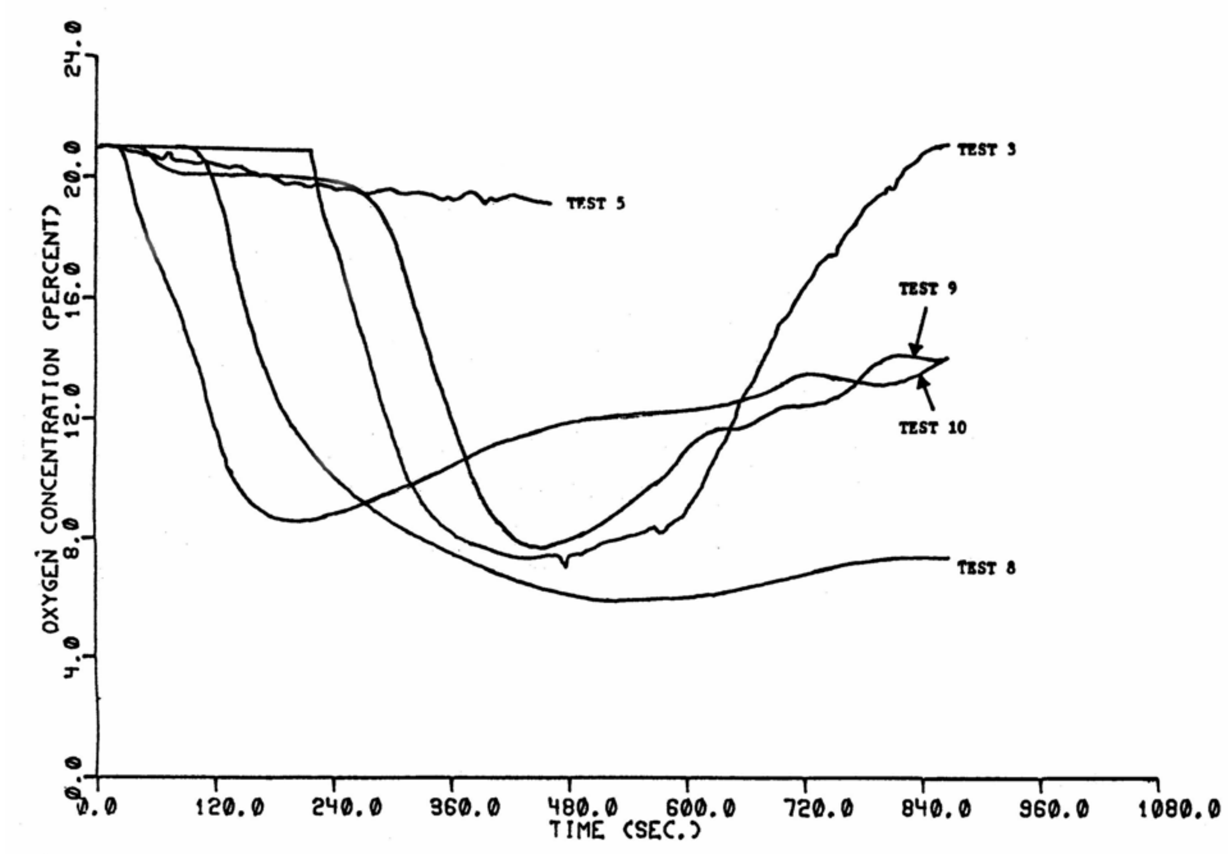


Figure 19. LD-3 container test oxygen concentrations. Test 5 represents the results from an aluminum container with a vinyl door covering, which burned through early in the test (from Blake, David R., *Evaluation of Fire Containment of LD-3 Cargo Containers*, DOT/FAA/CT-TN83/38, FAA Technical Center, October 1983).

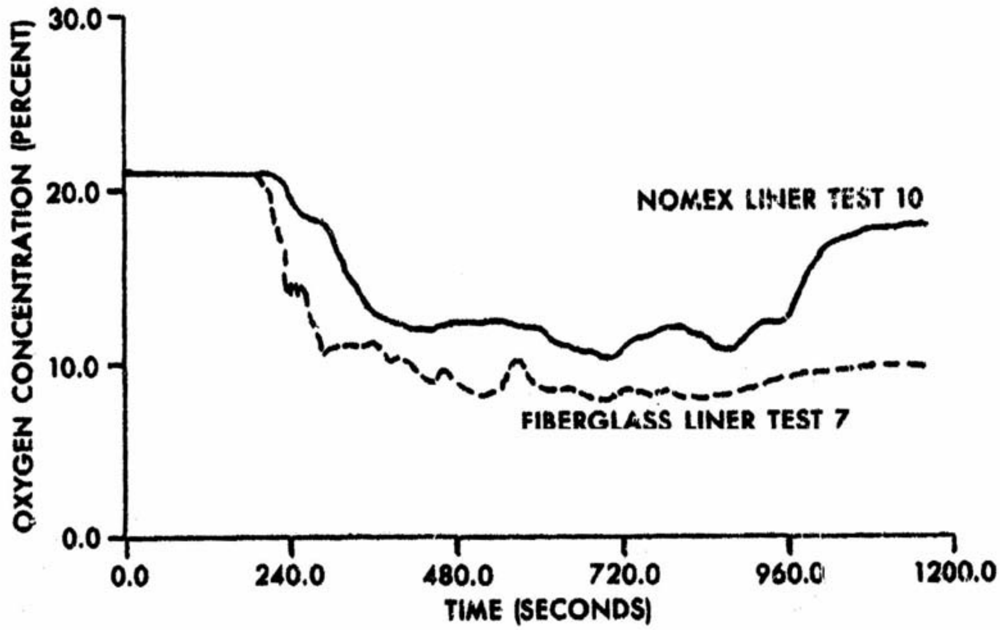


Figure 20. Oxygen concentrations measured during Class D compartment testing, with fiberglass and nomex/epoxy liner (from Blake, David R. and Richard Hill, *Fire Containment Characteristics of Aircraft Class D Cargo Compartments*, DOT/FAA/82-156, FAA Technical Center, March 1983).

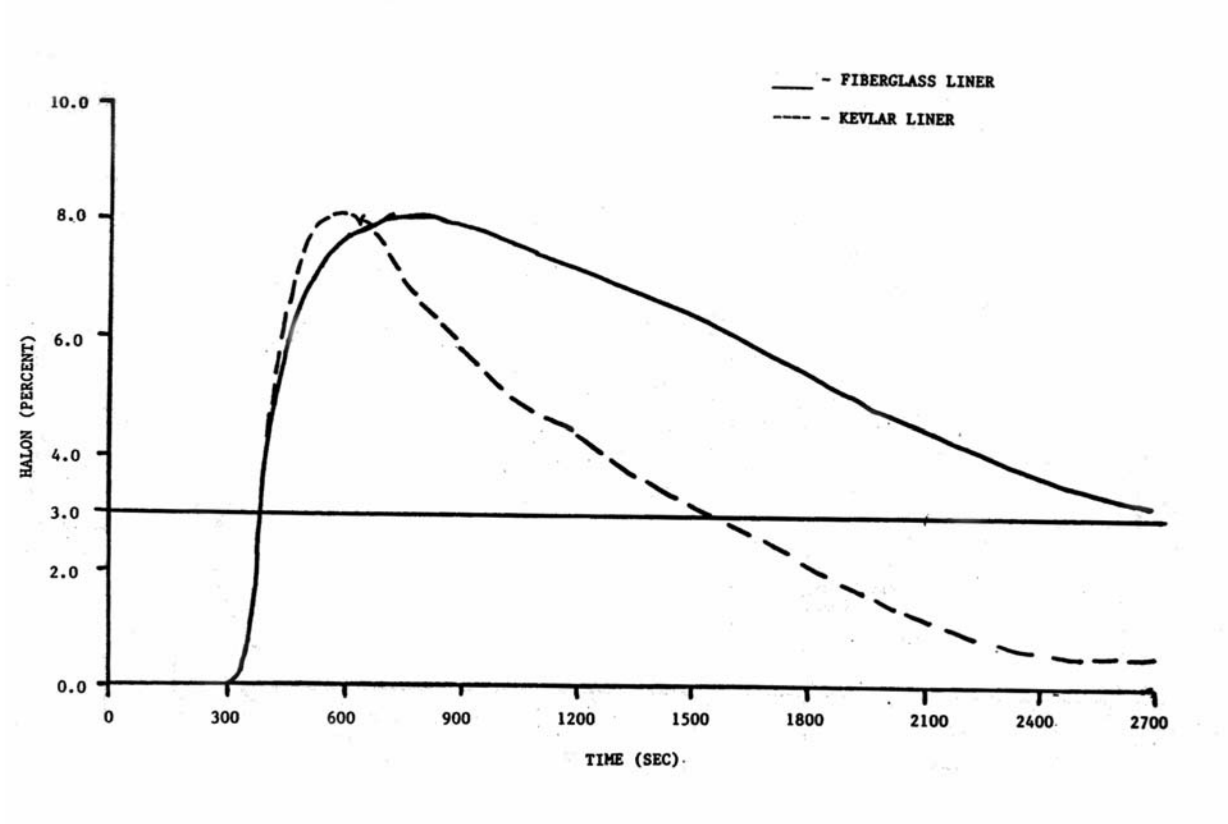


Figure 21. Class C compartment testing, Halon 1301 concentration (from Blake, David R., *Suppression and Control of Class C Cargo and Compartment Fires*, DOT/FAA/CT-84/21, U.S. Dept. of Transportation, FAA, February 1985).